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Archival Water-Level Measurements: Recovering Historical Data to Help Design for the Future

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14. ABSTRACT
This report discusses efforts to recover, digitize, quality assure, and analyze hundreds of station-years of lost-and-forgotten tide data and other water-level measurements that extend back to the early 19th century. Case studies are presented which show how such archival data can be used to retrospectively model historical extreme events, help validate ensemble-based models of flood hazard, or assess the effects of changing bathymetry. Therefore, the report demonstrates how data recovery can help engineers better characterize their water-level environment and understand long-term trends, resulting in better risk assessment and ultimately more robust design of new infrastructure and adaptation of existing infrastructure.

15. SUBJECT TERMS

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Archival Water-Level Measurements: Recovering Historical Data to Help Design for the Future

Stefan A. Talke[1], David A. Jay[1]

Executive Summary

Improving methods of assessing risk and designing structures to withstand extreme events and changing sea levels is a vital component of strategies for reducing risk to coastal resources and assets. An obvious approach to improving the statistical robustness of risk assessments is to increase the number, time span, and quality of available water-level data sets, and to assess trends and non-stationarity. In this report we discuss efforts to recover, digitize, and analyze hundreds of station-years of lost-and-forgotten tide data and other water-level measurements that extend back to the early 19th century. To date, more than 6,500 station-years of previously lost or forgotten tide data have been identified, of which more than 1,600 station-years have been recovered and more than 550 station-years digitized. An additional 500+ years of once-a-day river-stage measurements in tidal rivers have been recovered and digitized. Approximately 300,000 documents have been recovered.

In this report we also demonstrate how data recovery can help engineers better characterize their water-level environment and understand long-term trends, resulting in better risk assessment and ultimately more robust design of new infrastructure and adaptation of existing infrastructure. Long records help improve hazard estimates and can help characterize whether statistics are non-stationarity over climate-relevant time scales. Further, long and more complete records exhibit more natural variability and can be used to validate numerical simulations of historical storms (e.g., the 1893 New York hurricane). Historical tide data can help inform how tidal datums such as High Water and Low Water have changed, can be used to hindcast historical river flow, and provide a much richer view of long-term trends in local sea level. Used with numerical models, historical data help explain how anthropogenic activities have changed tide range and river slope, with the largest effects often observed far inland from the coast. Moreover, numerical models combined with tide data can be used to assess whether local engineering or other long-term changes have influenced storm surge risk. In conclusion, improved assessment of the past can help us better plan for the future.

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1. Introduction

Improving methods of assessing risk and designing structures to withstand changing sea levels is necessary to reduce risks to coastal resources and assets. Risk is usually assessed by estimating the likelihood that an extreme event will exceed a certain datum level and is weighted by the consequences. To account for changing sea levels, hazard assessments are often adjusted based simply on projections of changing sea level. Although often a good first estimate, such an approach is usually based on data of limited length from the National Oceanic and Atmospheric Administration (NOAA) or the United States Geological Survey (USGS), and/or may be based on gages located away from the location of interest. Moreover, approaches based on limited data may inadequately reflect natural variation, may incorrectly assume stationarity (i.e., that the natural variability of the past captures future variability), or may fail to consider non-linear feedback that affects future risk. These factors can be important: a recent study suggested that design heights for coastal dikes in Germany will need to increase at twice the rate of local changing sea levels to provide adequate protection in the future (Arns et al. 2017). Reasons included non-stationarity in tides and storm surge heights but were primarily driven by non-linear feedback between water depth and the height and period of waves.

An obvious approach to improving the statistical robustness of risk assessments and assessing non-stationarity is to increase the number and time span of data sets available at sites such as https://tidesandcurrents.noaa.gov. For example, by recovering data in archives, Talke et al. (2014) were able to double the length of the available New York Harbor tide record. Similar records exist for harbors and coastal regions all over the United States but remain lost and forgotten, stashed into various archives and poorly documented (Talke and Jay 2013). In this report we discuss efforts to document, recover, digitize, and analyze hundreds of station-years of lost-and-forgotten tide data that extend back to the early 19th century. To date, more than 6,500 station-years of lost tide data have been identified, of which more than 1,600 station-years have been recovered and more than 550 station-years digitized.

Archival tide measurements often represent data collected before the widespread alteration of harbors and rivers and thus form a snapshot that reflects the more natural functioning of these coastal systems. Such data are important for aquatic ecosystem restoration projects and provide insights into the potential efficacy of natural and nature-based coastal risk reduction infrastructure. Moreover, the measurements reflect earlier climate conditions and improve the possibility of characterizing changes to various portions of the water-level spectrum including storminess (e.g., Bromirski et al. 2003), individual storms, tides, and seasonality. Indeed, at some locations we are able to characterize changes to river flow, tidal properties, storm surge, and non-linear interactions (e.g., Moftakhari et al. 2013; Devlin et al. 2014; Talke et al. 2014).

To project forward in time and make better risk assessments (and ultimately build more robust infrastructure), research into the causes and consequences of non-stationarity and non-linear feedback is urgently needed. Therefore, we discuss here how historical data can be used in conjunction with hydrodynamic models to estimate the effects of changing bathymetry or changing sea levels on flood risk (e.g., Arns et al. 2017; Familkhalili and Talke 2016; Orton et al. 2016a, b). Ensemble-based modeling, improved boundary conditions, better resolution, bias-correction methods, and better parameterizations of turbulence are increasing confidence and predictive skill over time. In sum, we argue that the past is a preview; a better understanding of the past will help improve assessments of the future.

2. Data Recovery Efforts

2.1 History of Tide Measurements

The earliest modern tide measurements are thought to have begun in France (Brest), England (Liverpool), and The Netherlands (Amsterdam) in the mid-18th century. In the United States, the earliest data we have recovered is from Boston, Massachusetts, from the mid-1820s, though earlier measurements likely occurred to support bathymetric surveys, tide predictions in almanacs, and the sailing directions found in the American Coast Pilot (e.g., Furlong 1796).

Following a similar pattern as in England (Reidy 2008), early measurements appear to have been made by individual scientists and engineers such as Loammi Baldwin Jr. (1780–1838), who measured tides at the Boston and Norfolk Navy Yards, to define the height and depth of the first dry-docks in the United States (e.g., Freeman 1903). In the 1840s and 1850s, Alexander Bache began systematic measurements with the U.S. Coast Survey (USCG) (later the U.S. Coast and Geodetic Survey [U.S. C&GS] and now NOAA). By mid-century, the hydrographic surveys of the U.S. Navy also likely made short tide measurements in support of bathymetric surveys (e.g., Manning 1988).

The U.S. Congress ushered in an era of large-scale engineering of harbors with the River and Harbor Act of 1882. Public works, often undertaken by the U.S. Army Corps of Engineers (USACE), included jetty construction, channel deepening, flow diversion, diking and wetland reclamation, and other efforts. In many USACE districts, including Portland, Oregon; Charleston, South Carolina; Philadelphia, Pennsylvania; New Orleans, Louisiana; and New York, New York, significant effort was made to measure tides. These measurements supported bathymetric surveys and engineering projects but, just as important, helped define datum planes such as the Columbia River datum (see Hickson 1912). Tide gages were also needed at defense outposts (Smith 1997).

Around the turn of the 19th century, self-registering (automatic) tide gages (SRTG) became ubiquitous and widely disseminated. The U.S. Navy operated tide gages at various Navy bases (e.g., Bremerton, Washington; Boston; Portsmouth, Virginia; and Portsmouth, New Hampshire), and many cities appear to have made tide measurements in support of sewage plants (e.g., New York; Providence, Rhode Island; Boston). The U.S. Weather Bureau also appears to have used automatic gage recorders to measure water levels, including at tidal river locations. Similarly, some USGS stream gages (especially modern ones) are located in tidal rivers. During the mid-20th century, tide measurements were made by electrical utilities (e.g., at power plants such as Youngs Bay, Oregon) and other industries (see, e.g., Harris and Lindsay 1957). At the close of the 20th century and beginning of the 21st, data had been collected by various companies and state and federal governmental agencies, for example in support of shipping or Superfund efforts.

2.2 Brief Description of Archives—How and Where to Find Data

Though many tide data have probably been destroyed or lost to time, a surprising amount of data remains stored in archives. The brief survey of tide records given above provides clues about where to find extant paper records. In general:

- Many measurements made by the USCS and the U.S. C&GS (both agencies were predecessors to NOAA) are now found in the U.S. National Archives in College Park, Maryland, (Record Group 23 and 370). Records in the National Archives are considered safe from destruction.
- Some historical tide data are still under the control of NOAA and are currently stored at the Federal Records Center (FRC) in Suitland, Maryland. Many of these records, which include some data from the 19th century, will eventually be transferred to the National Archives. However, some risk of being lost or destroyed exists until that time.
- A number of 20th century NOAA records were copied to microfiche in the 1980s and recently scanned to PDF. These data, primarily spanning the 1920–1985 time period, are found in the EV2 database (Environmental Document Access and Display System, Version 2) at the National Centers for Environmental Information (NCEI): https://www.ncdc.noaa.gov/EdadsV2/
- Scientific records of the USACE were typically stored at local offices, rather than transferred to Washington, District of Columbia, (unlike the Coast Survey). Therefore, tide records measured by the USACE can be found:
    - At local offices. Tide data have been recovered from old filing cabinets in Portland, Oregon, and Albany, New York, with the help of knowledgeable local staff.
    - At FRC affiliated with the District. For example, a number of New York Harbor data were found at the FRC in Lee’s Summit, Missouri.
    - At a local office of the National Archives, in Record Group 77. Tide data from Mississippi, Louisiana, and Texas have been found at the National Archives in Atlanta,

Georgia, and Fort Worth, Texas. Similarly, New York Harbor data were found at the National Archives of New York.

- Early scientific measurements have been found in the personal archives of individual scientists and engineers. For example, early Boston measurements from 1825–1833 were found in the Baldwin family archives at the Harvard Baker Library, and in the Loammi Baldwin archives at the Massachusetts Institute of Technology.
- Tide records from the U.S. Navy or Weather Bureau may still exist in the U.S. National Archives or FRCs but have not yet been located. USGS tide records have been located at FRCs through help of local offices (e.g., the Portland, Oregon, office).
- Similarly, city and state archives may also contain tide records; these have also not yet been located.
- The International Hydrographic Review (IHR) report (IHR 1932) and the Works Progress Administration (WPA)-era Historical Records Survey (HRS 1937) document existing tide records held by federal agencies in the 1930s. The National Hurricane Research Project documented more than 600 tide-gage records on the Atlantic and Gulf Coasts during roughly 1900–1957 (Harris and Lindsay 1957). Such metadata are a useful tool for focusing research on specific regions. Tide data found in these sources and in the EV2 database have been concatenated into a database of known archival tide records.

Once produced by a federal, state, or local agency, scientific data currently follow a specific lifecycle, which is depicted in **Figure 1**. Data stored within an agency is most at risk for being lost because of moves, negligence, or disasters; for example, many scientific records from the USACE in New York were apparently lost during Hurricane Sandy, and historical tide data from the Charleston office were recorded to have been "eaten by vermin" in the WPA-era report. Records that are deemed important to a government agency, but are not required for day-to-day operation, are typically sent to an FRC and given a "disposal authority." These records are only available with permission from the originating agency. After a certain number of years, often 40 or 50 years, records marked as "permanent" are transferred from the FRC into the U.S. National Archives and Records Administration (NARA). While NARA records are publicly available to anyone, in practice finding records remains a challenge, primarily because data are only slowly cataloged.

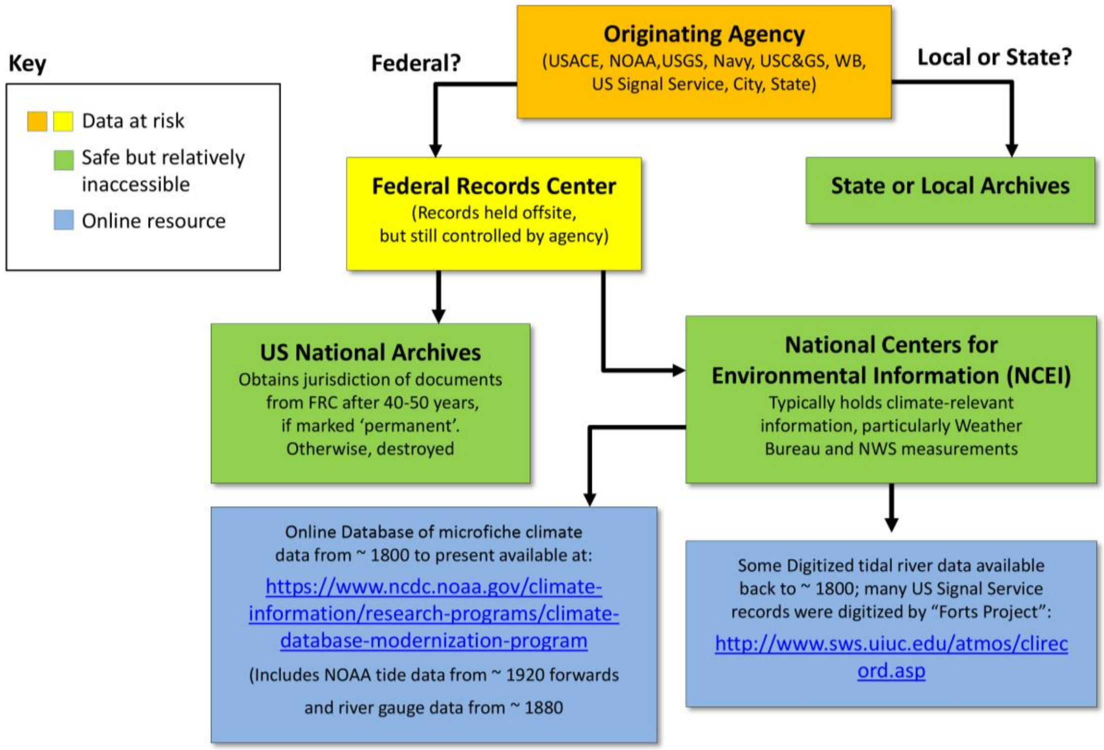


Figure 1. Flow of historic scientific data (including tide data) through the Federal government.

Some sleuthing is therefore required to discover and recover data from the FRC or NARA. Several approaches have been followed. First, NARA can be contacted for electronic finding aids for documents that are listed online; in some cases, this has yielded box lists of letters or hydrographic data, which can then help focus searches at an archive. Some finding aids are only available at the archives itself and can be photographed for later use. This is particularly true for FRC files; while the archives under FRC jurisdiction require agency permission to view, the accession records, known as Form 135s, are stored by the FRC and can be consulted and copied. The originating agency may also have saved its accession records. The accession number, once found, forms a key that can be used to trace the records as they move through the document lifecycle depicted in **Figure 1**. This method was successfully used to trace 19th century U.S. C&GS tide data from NOAA to the FRC to NARA.

2.3 Overview of Water-Level Data Recovered to Date

Overall, we have visited eight different offices of the National Archives, several different FRCs, NOAA headquarters, three USACE offices, and multiple local, city, and state archives in our effort to recover tide data. To date, we have taken approximately 230,000 photographs and downloaded >75,000 documents from the EV2 database. More than 1,600 unique “station-years” of tide data have been recovered, of which more than 550 station-years have been digitized. An additional ~500+ years of daily river-stage data have been recovered and digitized for the tidal portions of the Mississippi, Sacramento, and Columbia Rivers. Though our recovery work is extensive, our archival research shows that at least 5,000 additional station-years of tide data were collected and have not been found (>6,500 total). Though some records have undoubtedly been lost, past experience suggests that many data are in unprocessed states at various federal or local archives. Further, many 20th century records are in data formats (such as tape or punch-cards) that are not easily readable anymore, because of lack of specialized equipment (personal conversation, Albany, New York, office of the USGS).

Figures 2 through **8** provide a geographic glimpse of our recovery efforts to date. Of the records found, we have focused on digitizing (a) the longest, continuous records; (b) the oldest records; and (c) records at locations in which the largest physical changes to tides, river flow, and storm surge may have occurred, based on previous research. The oldest and most continuous records are found in the North Eastern States and Chesapeake Bay region (**Figure 2** and **Figure 3**) and include measurements from as early as 1825 in Boston and a continuous record in New York Harbor from 1844 forward (e.g., Governors Island, Sandy Hook, and Fort Hamilton data sets). Measurements in the South Atlantic Coast (**Figures 3** and **4**) and Gulf Coast regions (**Figure 5**) began in the late 1840s and early 1850s but were almost uniformly curtailed by the start of the Civil War in 1861. The exception is Old Point Comfort, Virginia, which remained in Union control throughout the war (**Figure 3**). After the war, measurements started again between 1875 and 1900 in response to growing interest in harbor engineering (e.g., the Rivers and Harbor Act of 1882). On the West Coast, long-term measurements began in the early 1850s in California (**Figure 6**) and Oregon (see **Figure 7**), moving to Washington, Alaska, and Hawaii in the 1870s and 1880s (**Figures 6–8**). Long term measurements began in the Philippines in 1900, and remote Pacific Islands in the 1940s (not shown). Thus, the expansion of U.S. interests on the West Coast (and elsewhere) is reflected in the start-date of tide gages. Similarly, the depression in the mid-to-late 1870s is correlated with the stoppage of many long-term gages, including Boston, New York, Old Point Comfort, and Astoria, Oregon.

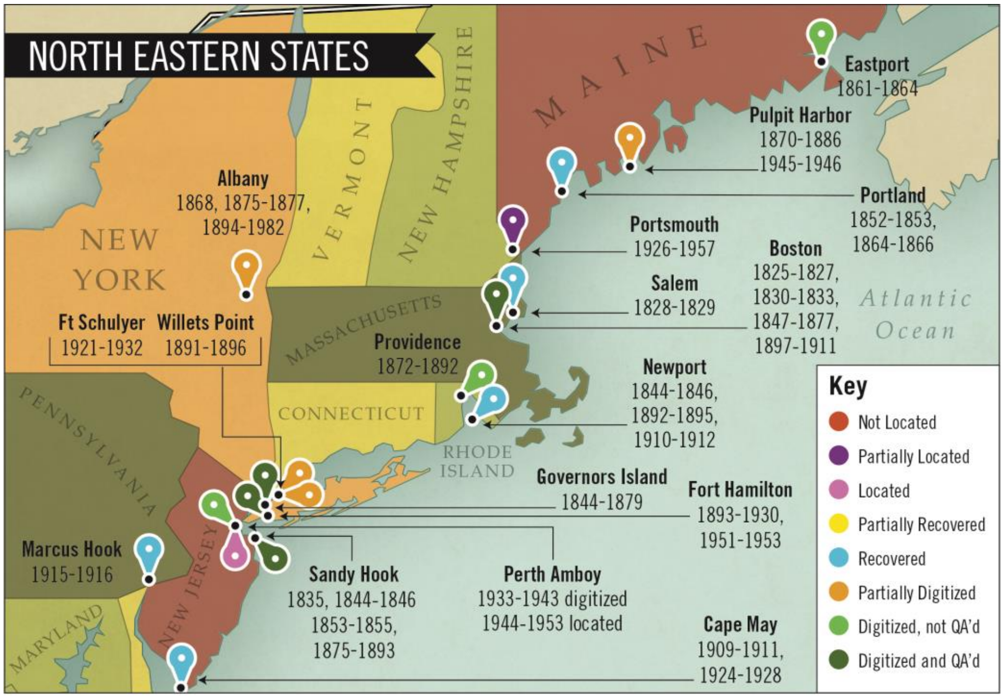


Figure 2. Historical tide data recovery efforts to date in northeastern United States. Dates refer to time periods in which high/low and/or hourly tabulations have been recovered. Typically, data before ~1860 is only available as high/low, while stations with both record types are increasingly common thereafter.

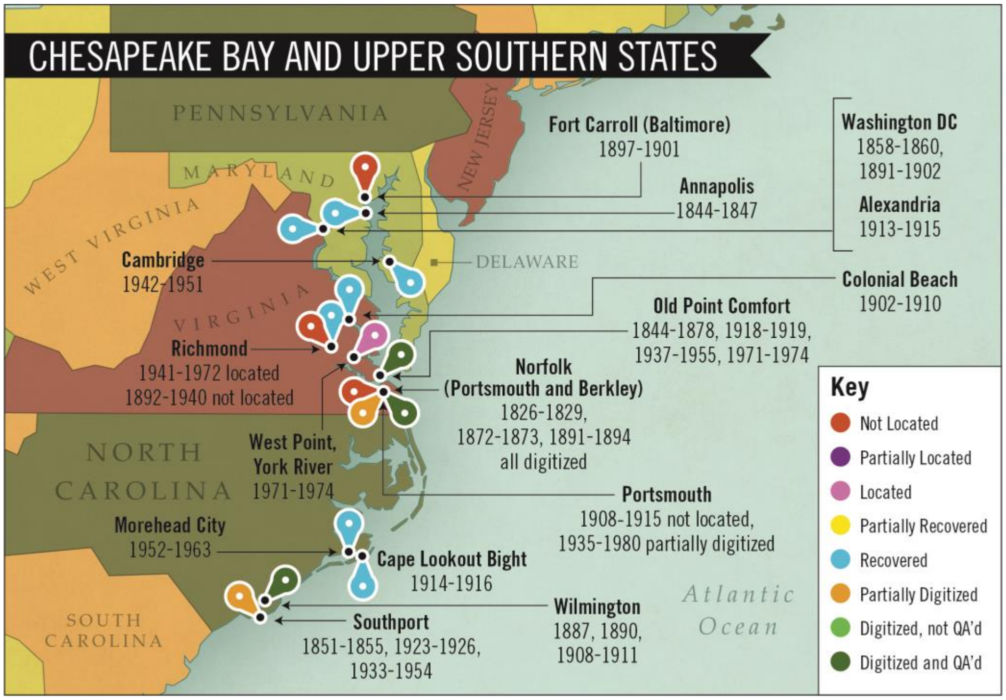


Figure 3. Historical tide data recovery efforts to date in the Mid-Atlantic region of the United States. See Figure 2 caption for details.

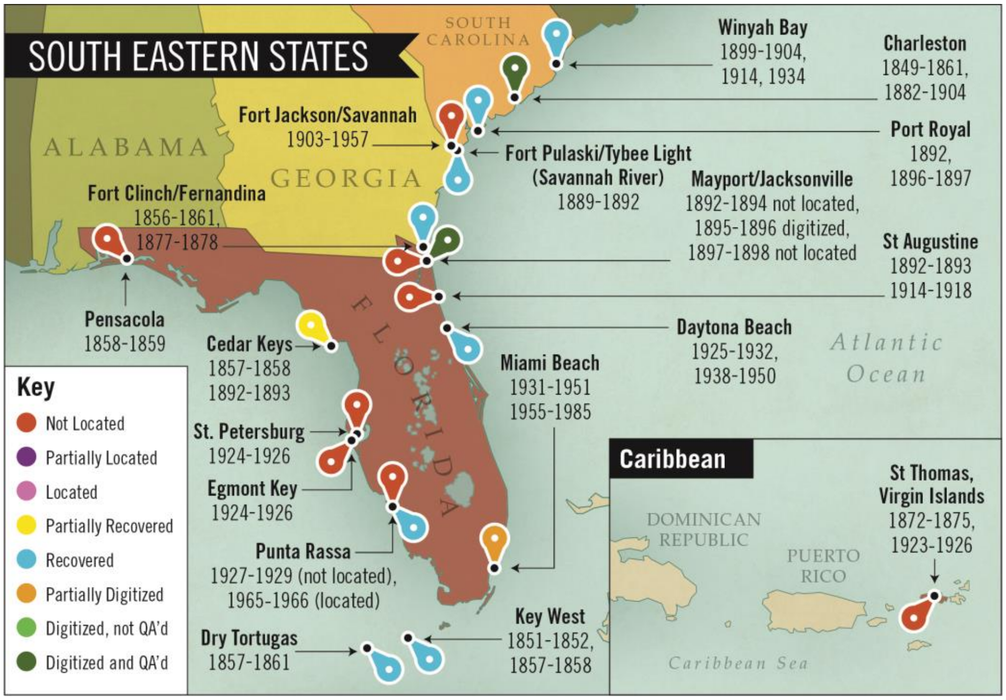


Figure 4. Historical tide data recovery efforts to date in southeastern United States. See Figure 2 caption for details.

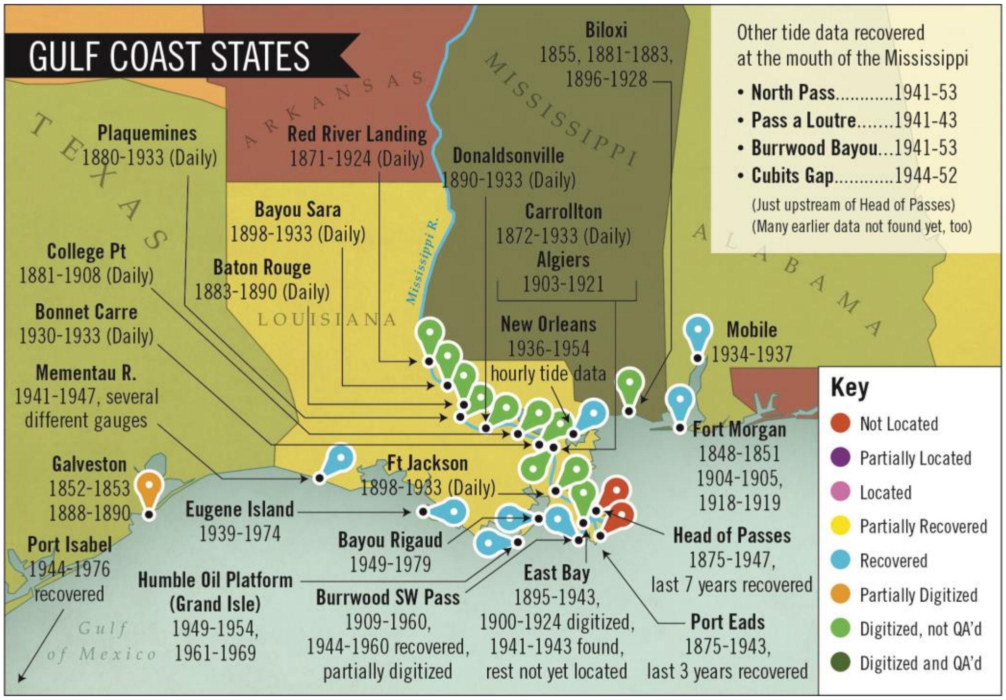


Figure 5. Historical tide data recovery efforts to date in the Gulf Coast of the United States. See Figure 2 caption for details.

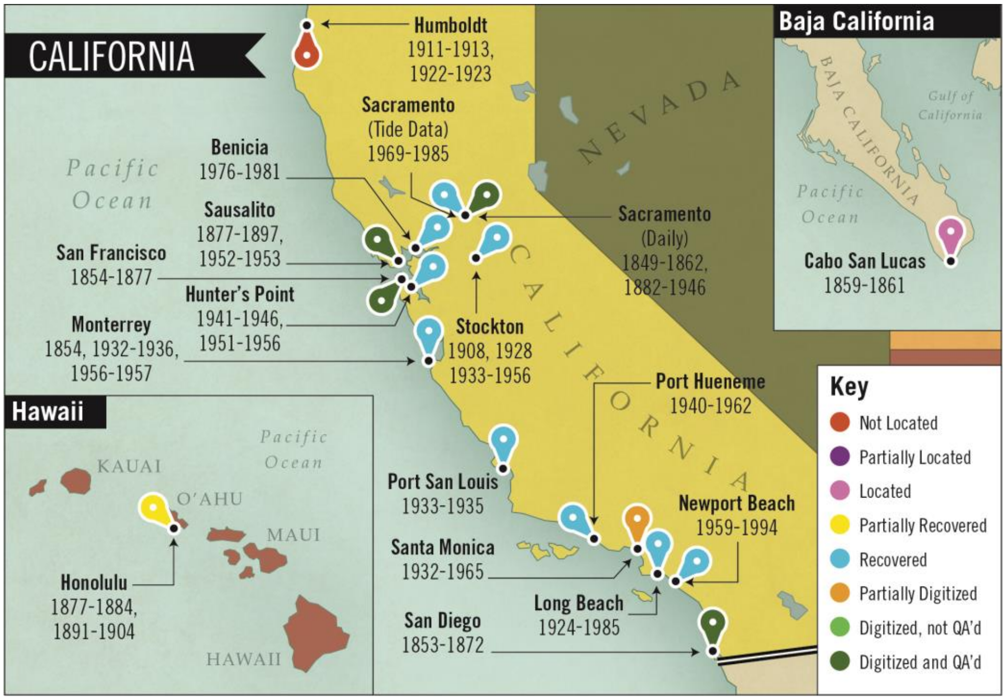


Figure 6. Historical tide data recovery efforts to date for California, Baja California, and Hawaii. See Figure 2 caption for details.

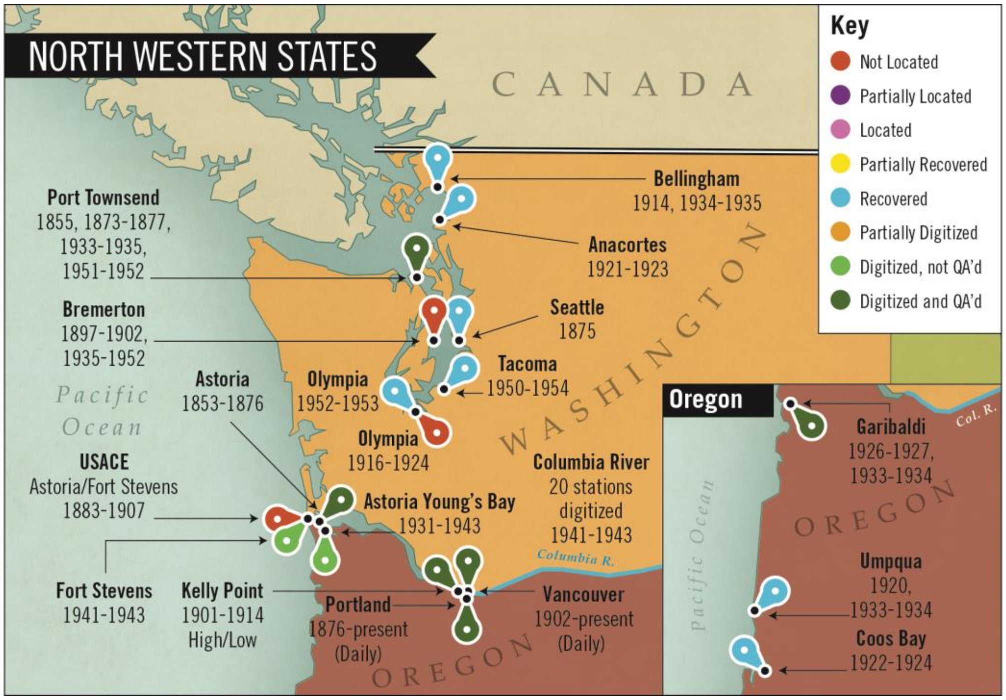


Figure 7. Historical tide data recovery efforts to date in northwestern United States. See Figure 2 caption for details.

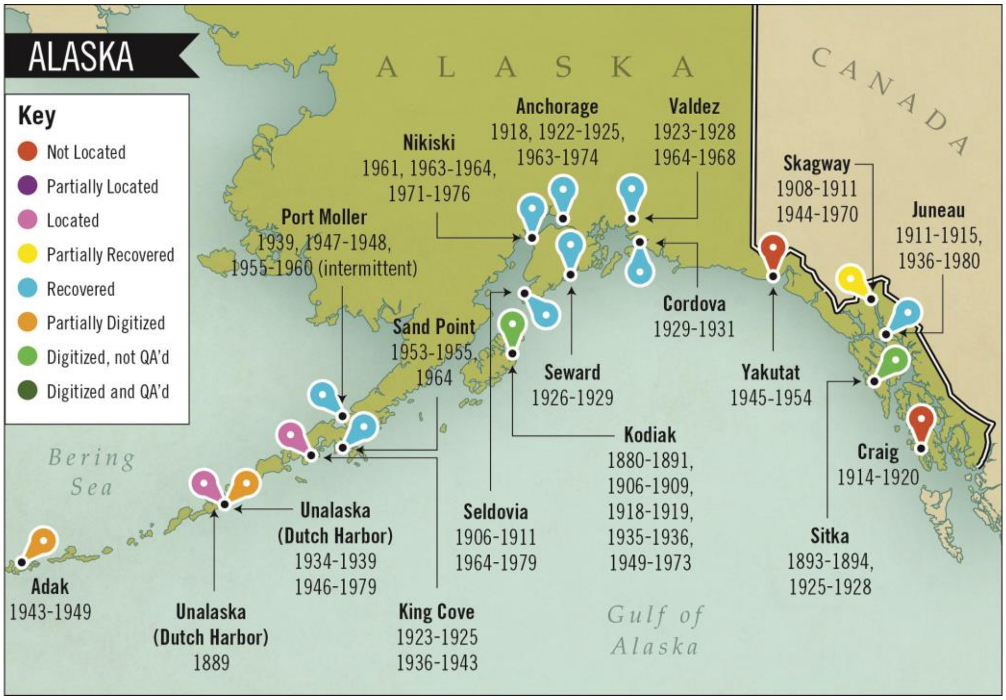


Figure 8. Historical tide data recovery efforts to date in Alaska.
See Figure 2 caption for details.

The longest and oldest 19th century records are from gauges that were located at important harbors and waterways, such as Boston (MA), New York (NY), Norfolk (VA), San Francisco (CA), the Columbia River (OR), and the Mississippi River (LA). The locations were important for commerce and shipping, civil infrastructure, and defense. Many records are found at military installations and reservations, and, in fact, the USACE and the USCS often cooperated in making measurements. Though the US C&GS restarted long-term measurements at these locations about 45–50 years later (e.g., Boston, Norfolk, Astoria), the long recording gap seems to have ensured that these records were never concatenated to modern tabulations.

In western Canada, measurements began in the 1890s. While a large proportion of measurements have been digitized, significant amounts of data remain undigitized in the form of marigrams at the Institute for Ocean Sciences in Sidney, British Columbia, or have not been located (Talke & Jay, 2013; **Figure 9**).

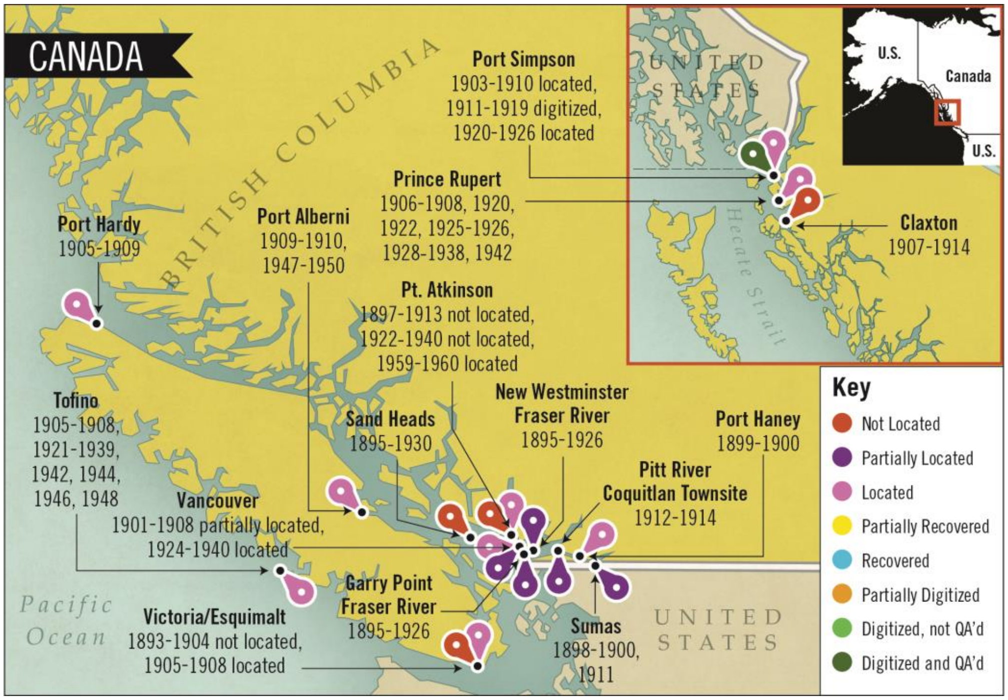


Figure 9. Record of undigitized historical measurements in western Canada (British Columbia).

In addition to 19th century records, a number of mid-20th century records have been recovered from the EV2 database. These are typically stations for which sea-level data may exist (e.g., Miami Beach), but which were discontinued before widespread use of computers. Hence, these data were never digitized by NOAA, unlike primary, still extant stations (e.g., Boston, Charleston).

Most of the records we have found are from NOAA and its predecessor agencies, the U.S. C&GS and the USCS. However, for some regions (e.g., from New York State) we have been fortunate to find some long high/low or hourly records from USACE records (**Figure 2**). Though most U.S. C&GS records have been found, a number of additional records have been located but remain to be recovered. This is particularly true of short records (6 months to year) from non-standard stations, or measurements from U.S. colonies such as the Philippines (e.g., Manila, 1900–1947) or Virgin Islands (St Thomas, 1872–1875). At least 500 station-years of unrecovered data from between 1870 and 1950 were therefore from outside the United States. After NOAA and U.S. C&GS data are exhausted, additional sleuthing to find USACE, Navy, USGS, and Weather Bureau records may yield additional finds (some of which are listed in red in the figures).

Finally, we note that archival research has also yielded daily stage measurements within tidal rivers, and ancillary data such as daily water temperature measurements or meteorological measurements. As an example, the tide observer at Astoria also measured water temperature and meteorological conditions for the Smithsonian.

2.4 Overview of Historical Tide Gages and Data

Early tide measurements were typically taken manually on a fixed staff gage with graduated marks (**Figure 10**) or using a box-gage, in which a tide staff moves up and down within a stilling well. Until the early 20th century, such manual measurements remained the primary method of estimating tides during bathymetric surveys. More than 400 boxes of such data (1835–1940) are available in the National Archives and include short-time series (1 week to 6 months) at every location where the U.S. C&GS ever made a chart.

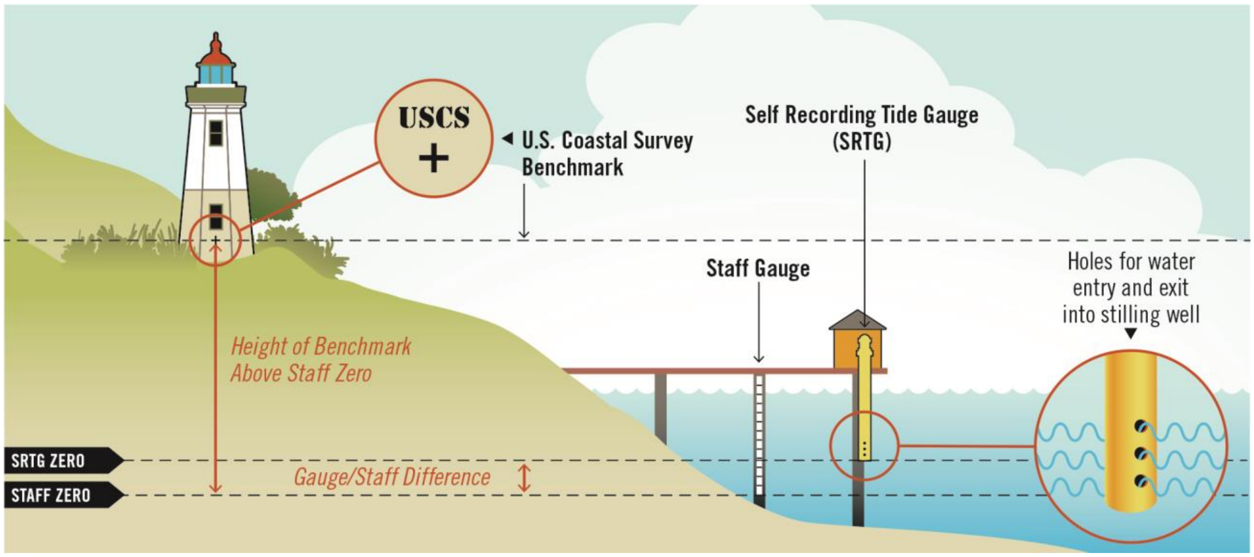


Figure 10. Schematic of a Self-Recording Tide Gauge (SRTG). Water entered and exited a stilling well as tides changed. This vertical motion was recorded by pencil on a scroll of paper which was moved forward (unwound) by a clock mechanism. The resulting tide trace was compared to independent measurements made on a graduated staff gauge. The zero of the staff gauge was leveled to a benchmark, which was typically etched into permanent structure such as a light house or geologic feature such as a rock.

Beginning in 1852, the USCS began using the SRTG designed by Joseph Saxton at permanent stations throughout the United States, including New York, Charleston, San Francisco, San Diego, California, and many other locations (Talke and Jay 2013; see also **Figures 2–8**). By producing a continuous pencil trace on a scroll of paper called a “marigram,” the automatic gages were able to measure phenomenon such as tsunamis that were not easily measurable by other means (**Figure 11**). One such tsunami, which arrived in San Diego and San Francisco on Dec. 25, 1854, after traveling from Japan, was used to estimate the depth of the Pacific Ocean and generated worldwide interest.

Though SRTG gages continued to be modified/improved over time, the basic setup for measuring tides remained the same between the 1850s and the early 1990s. A tidal station typically consisted of the SRTG, an external tide staff and/or box gage, and (in the 1850s) one benchmark set in a permanent structure such as a lighthouse or a geologic feature such as a large rock (**Figure 10**). More benchmarks were typically added later in the 19th/early 20th centuries and defined relative to the first. The SRTG and staff gage were typically set in a tide house on a dock, and the elevation of the staff zero was defined relative to benchmarks via leveling surveys. In the 20th century, the zero of the first tide staff of a gage series became known as the “station datum” and was propagated forward in time even when the tide staff was replaced and its zero changed. More recently, digital technology has replaced analog technology, resulting in fewer timing errors (e.g., Zaron and Jay 2014); however, other aspects of the measurement program, such as approaches to quality assurance, remain similar.

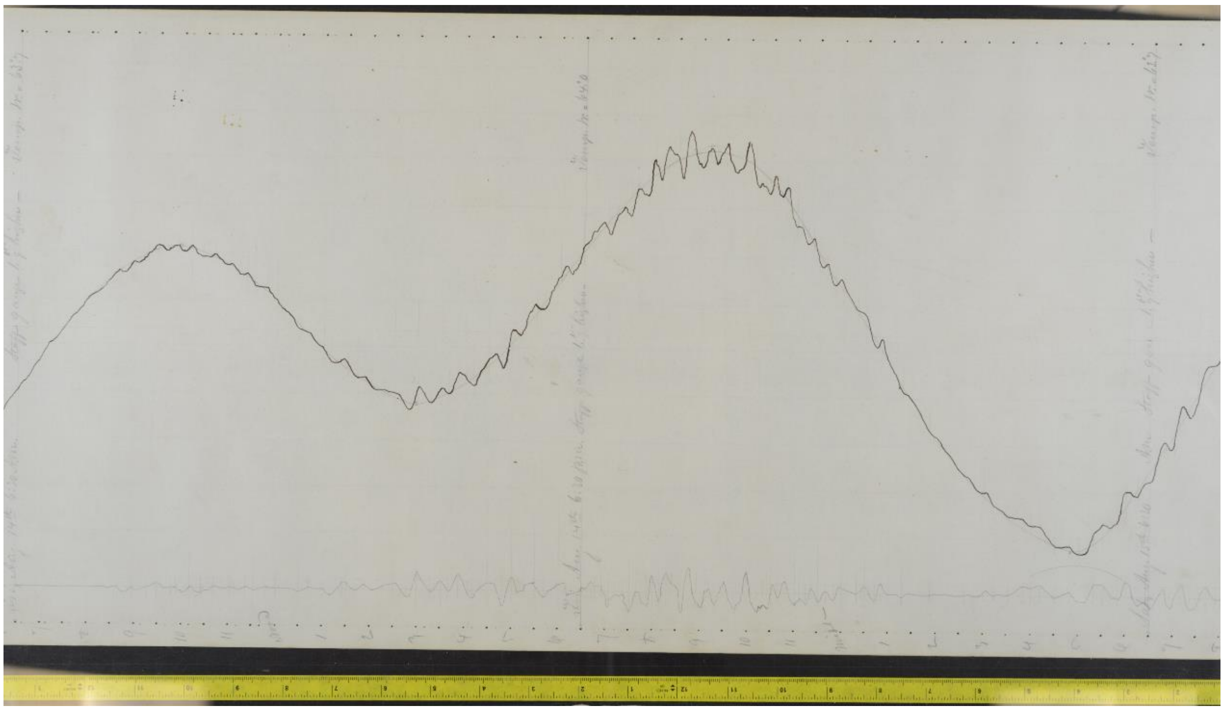
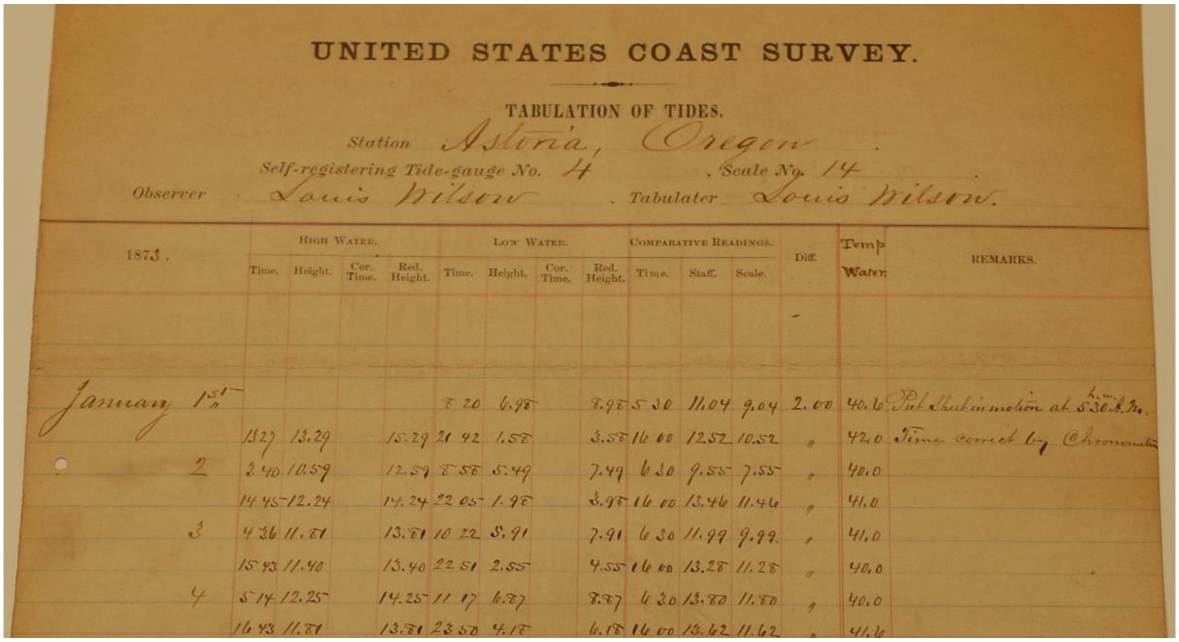


Figure 11. Example of a tsunami caused by the August 13th, 1868 Arica (Chile) earthquake, captured on the marigram roll at Astoria (OR) on August 15th.
Picture taken by S.A. Talke and P. Lau, US National Archives in Kansas City.

Generally speaking, leveling surveys between benchmarks and the primary staff occurred less systematically in the 19th century than in the 20th, often because of a paucity of leveling instrumentation or survey expertise. Over the 26 years of the Astoria gage, evidence of nine leveling surveys has been found; for other stations, fewer surveys have been recovered. In the 20th century, releveling appears to have occurred every 1–2 years (see Burgette et al. 2009). NOAA continues to frequently check the gages and makes annual leveling surveys to confirm data quality and diagnose any relative instability between the gage and its benchmarks.

To tie the 19th and 20th century SRTG measurement to the tide staff and therefore a benchmark, the external tide staff was typically read 10–60 times per month (depending on observer and weather conditions) and compared to the reading of the SRTG (see **Figure 12**). A constant offset indicated that the SRTG was working correctly, whereas variability indicated problems. Typical problems included siltation of the stilling well, clogging of the access holes, malfunction of the float, and expansion, contraction, wear, or warping of the various parts in the gage. Changes in the mean offset over time indicate changes to either the zero of the SRTG or the staff gage, for example after a gage move. The difference also changed when the SRTG was adjusted to prevent the pencil from running "off the chart" during storm conditions.


UNITED STATES COAST SURVEY.

TABULATION OF TIDES.

Station Astoria, Oregon.
Self-registering Tide-gauge No. 4 . Scale No. 14 .
Observer Louis Wilson . Tabulater Louis Wilson.

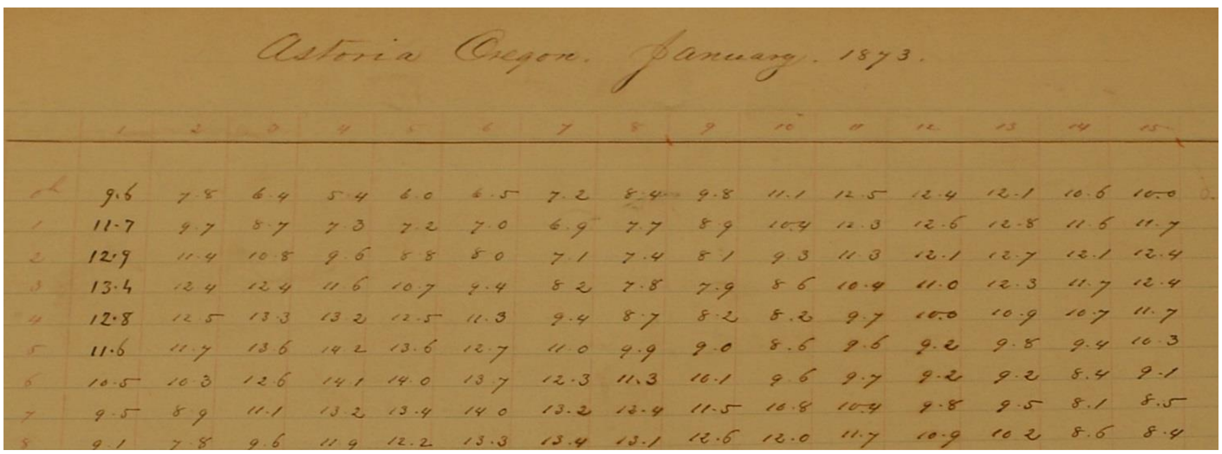
1873.	High Water Time.	High Water Height.	High Water Cor. Time.	High Water Red. Height.	Low Water Time.	Low Water Height.	Low Water Cor. Time.	Low Water Red. Height.	Comparative Readings Time.	Comparative Readings Staff.	Comparative Readings Scale.	Diff.	Temp Water	REMARKS.
January 1st					8 20	6.98		8.98	5 30	11.04	9.04	2.00	40.6	Put Stub in motion at 5.30 A.M.
	13 27	13.29		15.29	21 42	1.58		3.58	16 00	12.52	10.52	"	42.0	Time correct by Chronometer
2	2 40	10.59		12.59	8 58	5.49		7.49	6 30	9.55	7.55	"	40.0	
	14 45	12.24		14.24	22 05	1.98		3.98	16 00	13.46	11.46	"	41.0	
3	4 36	11.81		13.81	10 22	5.91		7.91	6 30	11.99	9.99	"	41.0	
	15 43	11.40		13.40	22 51	2.55		4.55	16 00	13.28	11.28	"	40.0	
4	5 14	12.25		14.25	11 17	6.87		8.87	6 30	13.80	11.80	"	40.0	
	16 43	11.81		13.81	23 50	4.18		6.18	16 00	13.62	11.62	"	41.6	

Figure 12. Example of high/low data and staff/SRTG comparisons, from Jan. 1873 at Astoria (OR). SRTG readings are denoted in the tabulation as a "scale reading," and were a constant 2ft below the staff reading. Notes indicated that the observer tabulated water temperature twice a day and checked the clock accuracy at the beginning of the month.

Each historical SRTG was geared to reduce the vertical tide fluctuation into a smaller fluctuation that would fit on an approximately 13-inch wide scroll of paper (e.g., the Astoria SRTG reduced the tides with the approximate ratio 14:1). In practice, the actual ratio of the gage did not exactly correspond to its stated ratio, because of, for example, manufacturing imperfections or wear. At the Astoria gage, extant notes and letters indicate that shrinkage or wear of the roller mechanism increased the scale from its original 14:1 to something more like 14.3 to 1. The observer adjusted for this by wrapping newspaper around the roller, an unorthodox but apparently successful solution. This example shows how important an attentive observer was to data quality.

Moreover, because paper rolls did not have a constant width, the SRTG feed mechanism was not reliable enough to have a paper-based zero datum. Therefore, a subset of the monthly staff/SRTG comparisons (typically about six staff/gage comparisons, according to extant records from San Diego and Sandy Hook, New Jersey) were used to estimate the actual scaling and zero of the tidal trace and reduce the marigram to high/low or hourly measurements. The mean staff offset was then used to reduce to a datum. As described by Agnew (1986), a similar practice continued until the (recent) introduction of digital gages and could lead to systematic bias of monthly sea-level records if improperly applied.

To enable tide predictions and define tidal datums, SRTG measurements were reduced to time series of high/low and hourly data (e.g., **Figure 12 & 13)** by either the local tide observer or a tidal "computer." Though observers were exclusively men until the 1920s, many of the tidal "computers" in Washington, DC, were women in the late 19th/early 20th centuries. A female observer has been documented for Charleston, in the 1920s, though there may have been others.



Astoria Oregon. January. 1873.

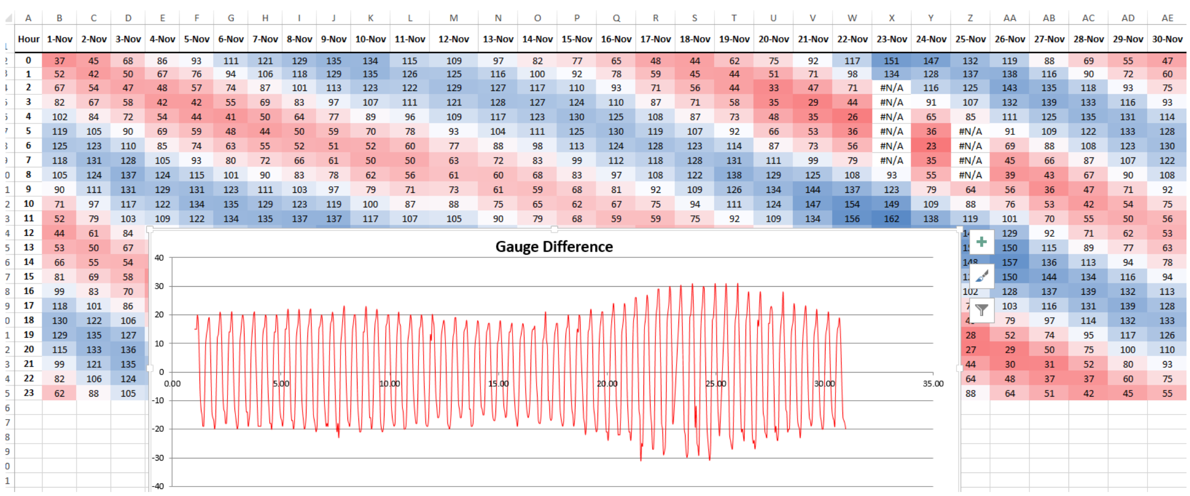
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
h	9.6	7.8	6.4	5.4	6.0	6.5	7.2	8.4	9.8	11.1	12.5	12.4	12.1	10.6	10.0
1	11.7	9.7	8.7	7.3	7.2	7.0	6.9	7.7	8.9	10.4	12.3	12.6	12.8	11.6	11.7
2	12.9	11.4	10.8	9.6	8.8	8.0	7.1	7.4	8.1	9.3	11.3	12.1	12.7	12.1	12.4
3	13.4	12.4	12.4	11.6	10.7	9.4	8.2	7.8	7.9	8.6	10.4	11.0	12.3	11.7	12.4
4	12.8	12.5	13.3	13.2	12.5	11.3	9.4	8.7	8.2	8.2	9.7	10.0	10.9	10.7	11.7
5	11.6	11.7	13.6	14.2	13.6	12.7	11.0	9.9	9.0	8.6	9.6	9.2	9.8	9.4	10.3
6	10.5	10.3	12.6	14.1	14.0	13.7	12.3	11.3	10.1	9.6	9.7	9.2	9.2	8.4	9.1
7	9.5	8.9	11.1	13.2	13.4	14.0	13.2	12.4	11.5	10.8	10.4	9.8	9.5	8.1	8.5
8	9.1	7.8	9.6	11.9	12.2	13.3	13.4	13.1	12.6	12.0	11.7	10.9	10.2	8.6	8.4

Figure 13. Excerpt of hourly tabulations of water level at Astoria (OR), from January 1873. Times from midnight (noted 0^h) to 23:00 were denoted in red on the left side of the sheet. Days of the month were noted in red across the top of the page. Comparison with high/low data and staff/scale comparisons (Figure 11) are often required to determine the datum of the data, particularly before 1873.

2.5 Digitization of Historical Records

The historical records described in Section 2.4 are being digitized at Portland State University. Data are keyed into Excel sheets, as shown in **Figure 14**, and basic quality assurance of the tabulation occurs immediately, as described below. Later, a more intensive quality assurance is undertaken (Section 2.6).

To catch large transcription errors, we use both a graphical approach and the conditional formatting option in Excel. Conditional formatting assigns a color to the data depending on whether it is large or small relative to others. The colors show that tides shift by about an hour each day (**Figure 14**), forming a diagonal pattern of high water (blue coloring) and low water (red coloring). The magnitudes of the tides also vary over the 2-week spring-neap cycle. By this visual feedback, large transcription errors become obvious as anomalies in the color pattern and can immediately be corrected. Moreover, we automatically plot the data and its time derivative, both of which should follow a sinusoidal pattern and be relatively smooth and free of discontinuities in water level. For example, a change of water level of several meters in 1 hour is unlikely to be physically caused and may show up as a positive spike in the time derivative graph, followed by a negative (return to normal conditions). Most tabulation errors or datum shifts are less obvious than the aforementioned example, and short-term, non-sinusoidal (i.e., non-astronomical) fluctuations in the rate of water-level change can sometimes be caused by storm surge or coastally trapped waves, in addition to gage errors. For this reason, quality assurance in the digitization phase is concerned primarily with catching obvious errors, and more intensive quality assurance is done at a second stage (see Section 2.6).



A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE
Hour	1-Nov	2-Nov	3-Nov	4-Nov	5-Nov	6-Nov	7-Nov	8-Nov	9-Nov	10-Nov	11-Nov	12-Nov	13-Nov	14-Nov	15-Nov	16-Nov	17-Nov	18-Nov	19-Nov	20-Nov	21-Nov	22-Nov	23-Nov	24-Nov	25-Nov	26-Nov	27-Nov	28-Nov	29-Nov	30-Nov
0	37	45	68	86	93	111	121	129	135	134	115	109	97	82	77	65	48	44	62	75	92	117	151	147	132	119	88	69	55	47
1	52	42	50	67	76	94	106	118	129	135	126	125	116	100	92	78	59	45	44	51	71	98	134	128	137	138	116	90	72	60
2	67	54	47	48	57	74	87	101	113	123	122	129	127	117	110	93	71	56	44	33	47	71	#N/A	116	125	143	135	118	93	75
3	82	67	58	42	42	55	69	83	97	107	111	121	128	127	124	110	87	71	58	35	29	44	#N/A	91	107	132	139	133	116	93
4	102	84	72	54	44	41	50	64	77	89	96	109	117	123	130	125	108	87	73	48	35	26	#N/A	65	85	111	125	135	131	114
5	119	105	90	69	59	48	44	50	59	70	78	93	104	111	125	130	119	107	92	66	53	36	#N/A	36	#N/A	91	109	122	133	128
6	125	123	110	85	74	63	55	52	51	52	60	77	88	98	113	124	128	123	114	87	73	56	#N/A	23	#N/A	69	88	108	123	130
7	118	131	128	105	93	80	72	66	61	50	50	63	72	83	99	112	118	128	131	111	99	79	#N/A	35	#N/A	45	66	87	107	122
8	105	124	137	124	115	101	90	83	78	62	56	61	60	68	83	97	108	122	138	129	125	108	93	55	#N/A	39	43	67	90	108
9	90	111	131	129	131	123	111	103	97	79	71	73	61	59	68	81	92	109	126	134	144	137	123	79	64	56	36	47	71	92
10	71	97	117	122	134	135	129	123	119	100	87	88	75	65	62	67	75	94	111	124	147	154	149	109	88	76	53	42	54	75
11	52	79	103	109	122	134	135	137	137	117	107	105	90	79	68	59	59	75	92	109	134	156	162	138	119	101	70	55	50	56

Hour	1-Nov	2-Nov	3-Nov	25-Nov	26-Nov	27-Nov	28-Nov	29-Nov	30-Nov
12	44	61	84	[illegible]	129	92	71	62	53
13	53	50	67	[illegible]	150	115	89	77	63
14	66	55	54	148	157	136	113	94	78
15	81	69	58	[illegible]	150	144	134	116	94
16	99	83	70	102	128	137	139	132	113
17	118	101	86	[illegible]	103	116	131	139	128
18	130	122	106	[illegible]	79	97	114	132	133
19	129	135	127	28	52	74	95	117	126
20	115	133	136	27	29	50	75	100	110
21	99	121	135	44	30	31	52	80	93
22	82	106	124	64	48	37	37	60	75
23	62	88	105	88	64	51	42	45	55

Figure 14. Example of a table of hourly digitized data, from Boston in Nov. 1870. Values were multiplied by ten to avoid an extra key stroke. "Conditional Formatting" is used to visualize the daily pattern of tides and quickly find and fix outliers and typos. A plot of the data as well as the gauge difference were shown to automatically detect errors.

Digitizers are also instructed to transcribe any notes on data quality into a notes section, and indicate time periods of known issues. During time periods of gage malfunction, historical observers often interpolated the data, for example based on tide tables. Such data were typically written in a different color or put in parenthesis (Talke and Jay 2013). Obvious interpolations or other errors in the original tabulations are replaced with a “NaN” in the spreadsheet, indicating that no reliable measurement was obtained.

For some records, the only data available are the original marigrams. For this data, we have written a software program that produces high-resolution data. In the program, a line-finding algorithm tracks the pixel coordinates of the pencil trace. Next, the pixel coordinates of known (time, height) points are defined manually by clicking on the image. After correcting for the known barrel distortion of the lens, the pencil trace is scaled into time/height coordinates. Various quality assurance steps are necessary to account for problems in the digitization. Though labor intensive, this process can result in a usable digital data set. For example, we processed Astoria data with a 1-minute resolution for the years 1855 to 1870. Approximately 200 months of data, each with 60–70 images covering 1 foot of a marigram, were processed.

2.6 Quality Assurance of Data

Data quality is evaluated qualitatively and quantitatively, and the data itself along with extant letters, notes, and qualitative evaluations are used to increase confidence in the data quality. Therefore, our approach has been to build a case history of each gage based on both qualitative and quantitative data. Contemporary notes and letters provide a chronology of each gage and can help identify particularly problematic time periods, caused, for example, by gage malfunction, a change in observer, settling of the dock, silting of the gage site, or any of myriad reasons. While laborious, we find that this approach can identify datum shifts, explain missing data, and generally improve the level of trust in the data. Extensive case histories and document case files are available for Astoria, Boston, Old Point Comfort, and Charleston. Information for many other stations such as San Diego; Governors Island, New York; Sandy Hook; Pulpit Harbor, Maine; and Providence exist but are still being organized.

Early tide gages were often located in remote locations and observers faced many challenges. Extant letters and notes indicate that ships often jarred the docks or knocked into the gage house, often stopping the clock mechanism or damaging the instrument. The clock mechanism was often fast or slow and required constant adjustment by chronometer or through sextant observations. Instruments were sometimes damaged or lost in storms, and ice often froze the gages in winter. “Worms” and other biota often rotted the staff gages or dock piers after several years, requiring continuous vigilance, repairs, and occasional gage moves. Zinc was required to reduce rust. Sedimentation caused by anthropogenic development or floods occasionally affected measurements and required dredging and/or gage moves (e.g., in Astoria and Boston). Under such conditions, the character, education, and reliability of the tide observer played an outsized role in gage quality. From extant notes and letters, it is clear that observers in Astoria and Pulpit Harbor were of exceptional quality, whereas the observer at Castle Pinckney, South Carolina from 1852–1855 was of poor quality. Most observers were somewhere in between and produced periods of good data interspersed by occasionally questionable data.

Aside from these qualitative evaluations, we have applied several quantitative techniques to catch errors in our digitization and in the original tabulations. Some expert judgment is often required to determine whether a measurement error has occurred. Errors are replaced with a NaN in the spreadsheet; however, when it is unclear whether data are erroneous or real, we have left the data as is, to avoid inputting our own bias and interpretation. Among the methods used to make a more thorough quality assurance are:

- Outlier identification and datum shifts. To identify outliers in data and transcription errors, we use several approaches. As discussed earlier, data tabulations are color coded by magnitude, such that discontinuities are quickly observed. Similarly, we carefully assess that no unrealistic discontinuities occur in H(t), (the tabulated height), and its first and second derivatives. For example, a sudden, temporary decrease in dH/dt to zero during peak-ebb (indicating stationary water levels), followed by a spike (indicating a fast drop), is suspicious and would be flagged for checking. In addition, we look at the residual time series that results after the predicted astronomic tide is removed and identify non-meteorological spikes and discontinuities. Finally, we have been experimenting with wavelet-based methods of identifying incorrectly sampled data.
- Error Checks. To identify time periods with clock or stilling well errors, we are using a modified version of the technique suggested in Agnew (1986) and Hudson et al. (2017). In this technique, the difference between the predicted and measured tide is regressed against dH/dt, a measure of how fast the tide is changing. Because SRTG errors were largest when dH/dt was large, any large slope in the regression suggests either timing errors or problems with the stilling well (basically, the water level in the well and the actual water level do not agree).
- Data comparisons. As discussed in Section 2.4, three primary types of data were produced by the SRTG—the staff/gage comparisons, high/low measurements, and hourly data. For time periods in which the measurements overlap (e.g., when the daily comparison occurred at high water, or when the high water occurred on the hour), we can estimate the difference. The results are then aggregated over time and the statistics analyzed. This approach has yielded some interesting results; for example, a persistent bias of ~0.01m was found between high/low measurements and the daily comparisons in Astoria. This bias in the high/low data is corrected when reducing to a modern datum, and when assessing sea level.
- Buddy gage approach. When more than one gage is available, comparisons of nearby (“buddy”) gages can be used to infer data problems such as datum shifts, using the techniques described above. For example, multiple small datum shifts and evidence of dock settling in the Governors Island measurement were identified by comparing with Brooklyn measurements. Similarly, an error in the 1925–1960 station datum used in Astoria was

identified through examination of original leveling surveys and staff/gage comparisons, and by comparing the data with a nearby gage recovered at Astoria Youngs-Bay (1931–1943).

- Redundant digitization. For many stations, we have digitized duplicate copies of the same data. Comparison of the data is then used to catch any transcription errors; however, this method cannot detect errors in the original data.

Datum shifts in data can be found by the analytical methods and by archival research. Periods of gage problems or gage movement can then be identified, often along with quantitative statements about changed staff heights or datum. Confirmed datum shifts are then applied to the data as a correction (see also Section 2.7 and 2.8).

Although the quality assurance described above has primarily been applied to historical data, we note that they can be used to quality assure more modern data. In fact, these techniques have identified a year of questionable tide data in Astoria, beginning in May 1948. Similarly, data from the early 1970s in Boston (and other U.S. locations) show evidence of timing and quality issues (e.g., Ray and Foster 2016). As is supported by extant gage notes and comparisons, our qualitative impression is that data quality in the 1870s was often better than the 1970s. A systematic reevaluation of digitized tide data, using the techniques described here, is probably warranted.

2.7 Benchmark and Datum Recovery

Just as some actual SRTG measurements have been lost and forgotten, the original metadata used to reduce historical gage data to a datum is often difficult to find. However, a surprising amount of information can be found by first understanding which agencies used benchmarks and leveling, and why. This information provides clues about which archives to visit and search.

First and foremost, the U.S. C&GS used permanent tide stations and benchmarks to define careful leveling networks, with vertical elevations referred to tidal datums such as Mean Low Water (MLW) or Mean Sea Level (MSL), often used interchangeably with Mean Tide Level in the 19th century. First used primarily in the production of bathymetric maps of harbors and coastal regions, the U.S. C&GS gradually expanded its purview to include topographic surveys. In the late 19th and early 20th century, the newly formed USGS also began topographical surveys, typically using MSL (tide level) as a datum (e.g., Manning 1988). The USGS also used the tidal datums from the U.S. C&GS as a reference (e.g., in Oregon). More locally, the USACE also defined benchmarks and made leveling surveys in support of engineering projects (such as the construction of the Columbia River jetty between 1881 and 1917). State, city, and county engineers often produced their own networks of benchmarks and datum, but occasionally tied them into the federal datum (e.g., in New York and Boston).

Given the history detailed above, information about historical datum, leveling surveys, and benchmarks can be found in the following sources:

- NOAA. NOAA keeps a record of benchmark heights, leveling surveys, and staff heights for most of its stations. However, 19th century records are often incomplete and require additional investigation.
- Historical reports, including annual reports of the U.S. C&GS, USGS, and USACE and/or local reports produced by federal agencies such as the Hickson (1912) report on the Columbia River datum. Other sources of information include state reports or local reports made in preparation of engineering works such as the Charles River Dam in Boston (e.g., Freeman 1903). Many of such reports are available online, but some must be obtained from local libraries and archives.
- Historical letters and correspondence. Important letters regarding the management of the tidal division of the U.S. C&GS are available in the U.S. National Archives and contain information about historical leveling surveys, benchmark heights relative to staffs, and other gage information. In many cases, historical letters of the USACE were also saved, but finding data is more difficult because there was no specific "Tidal Division" and relevant records may be mixed with general records.
- Original engineering notebooks. Some of the original leveling notebooks of the U.S. C&GS are available at the National Archives. Similarly, USGS notebooks have been saved and are located in Denver, Colorado. In some cases, survey books for the USACE have also been saved.

2.8 Tying Historical Water-Level Measurements to Modern Measurements

Historical time series such as Astoria (1853–1876) are often separated from modern data by multiple decades. As a result, the original benchmarks have often been lost, destroyed, or compromised over time, complicating interpretation of historical sea level. To tie historical data to modern data, therefore, a case-history approach is first required in which all known historical and modern benchmarks are cataloged and their relative heights to each other assessed at different snapshots in time. Because many benchmarks are unstable, particularly in coastal regions, the relative heights between benchmarks may change over time. The National Geodetic Survey typically flags unstable benchmarks. Still, professional judgment is often needed to assess the quality and stability of benchmarks.

Leveling errors and the differential vertical velocities of benchmarks can result in different estimates of historical sea level, depending on which benchmark is assumed to be most representative of local vertical land motion. To reduce subjectivity and assess the consequences of different interpretations, we advocate tying historical data to multiple benchmarks, thereby obtaining an ensemble of possible historical sea levels. An example of this approach is shown in **Figure 15**, in which two different approaches to connect the historical Astoria data set to the modern North American Vertical Datum datum (NAVD-88) are assessed. In this “stick figure,” the relative height of USE (U.S. Army Corps of Engineers) A-1, a historical benchmark, is given relative to the staff zero in 1873. Although the USE-A1 benchmark was destroyed in 1931, its height relative to a stable benchmark, X100, was made in 1930. This benchmark, in turn, still exists with a known offset to NAVD-88. Put together, this suggests that the staff zero in 1873 was 4.84 ft. below NAVD-88.

Another possible way to connect 19th century data to the modern NAVD-88 datum is through comparison with a local datum, for example through a city datum such as Boston Base or through the “station datum” maintained at an individual tide gage (such local datum are often composites of many benchmarks and should, if correctly maintained, be more stable than an individual benchmark). As an example, we connect the 1873 staff in Astoria to the station datum of the modern Astoria-Tongue Point tide measurement (1925–present). In this case, our research corroborates the Burgette et al. (2009) conclusion that the station datum was unstable between1925 and 1960. Correcting for this error, we use the tabulated difference between USE-A1 and the station datum (Rappleye 1932) to obtain a second estimate of a 4.92 ft. offset between the historical gage zero and NAVD-88. The two estimates in **Figure 15** are then averaged to obtain an average datum tie. Such estimates, possibly combined with other scenarios, can be combined to produce the most likely connection between historical and modern data, along with an estimate of the possible bias and error.

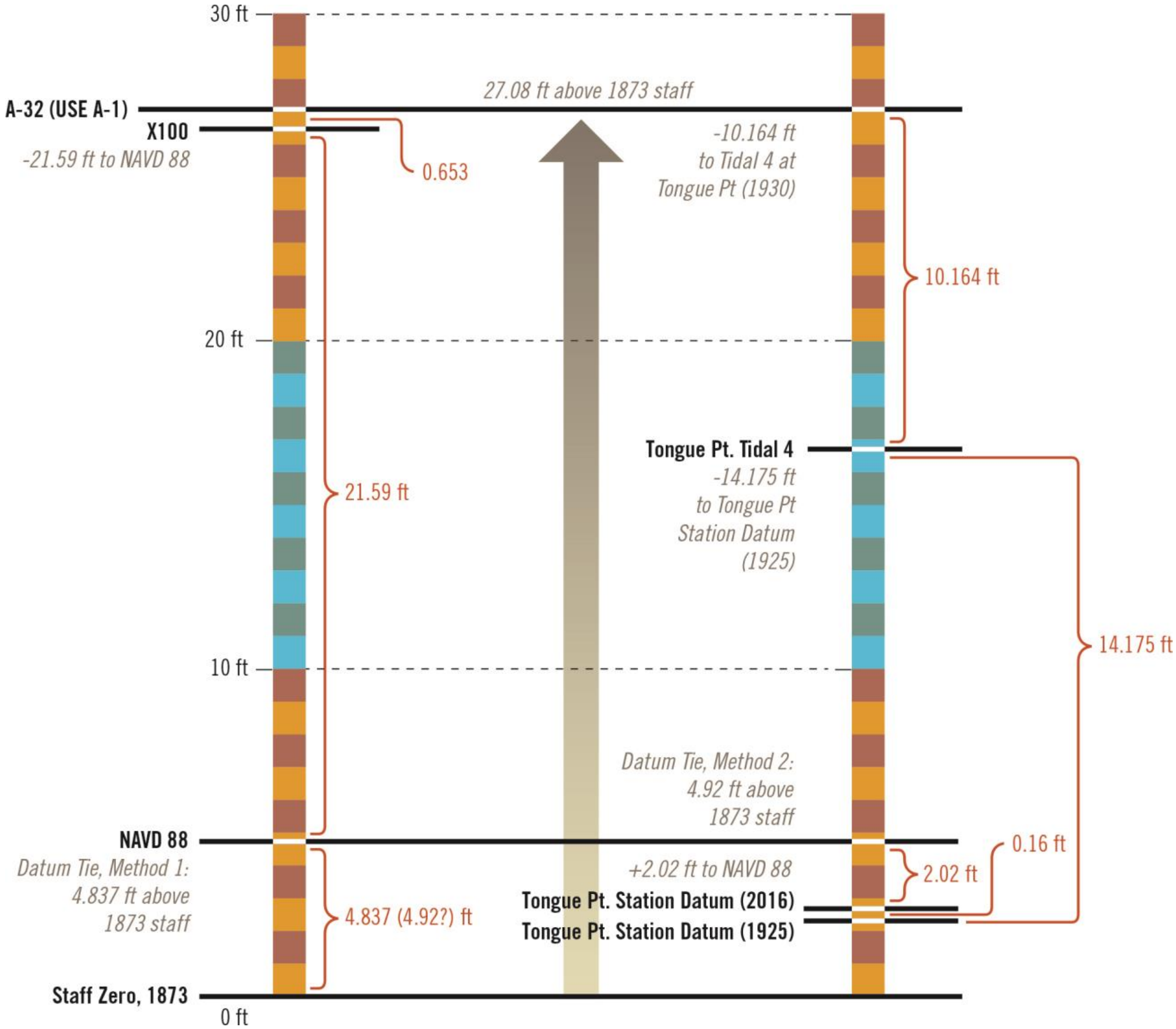


Figure 15. The stick-figure approach, applied to Astoria data. On the left-hand side, the height of benchmark A-32 relative to both the 1873 staff and the X100 benchmark in 1930 has been found using archival research. While A-32 has been destroyed, the height of X100 relative to NAVD-88 is known. Put all together, the historical staff is connected to the modern datum. On the right-hand side, the relative height difference between Tidal 4 and A-32 was known, as was the height of Tidal 4 relative to the 1925 station datum. After applying a 0.16ft offset to account for drift in the station datum (see Burgette et al., 2009 and this report), and using the known height of the modern station datum to NAVD-88, another estimate of the NAVD-88 height of the 1873 staff zero is obtained. Multiple estimates (such as described here) provide an estimate of possible bias and uncertainty.

3. Data Analysis: What Are Water-Level Measurements Good For?

Archival tide measurements, which at some locations go back to the middle or even early 19th century, occurred before the widespread alteration of harbors and rivers and during earlier climate conditions at the end of the cool climate period known as the Little Ice Age, which occurred from roughly 1300 until 1850–1900. Thus, recovered measurements form an instrumentally based snapshot of the natural functioning of coastal systems. Moreover, these data sometimes provide information about the “storm of record,” and, through their long length, enable analysis of decadal and century-scale variability and trends.

3.1 Reconstructing Historical Extreme Events

Planning for extreme events often takes into account the most extreme measured event; for example, the 1938 hurricane remains the “storm of record” for some locations in Rhode Island and Connecticut and informs design requirements. However, in many cases the most extreme events predate modern measurements, and extreme water-level elevations are poorly known or ambiguous.

Data recovered from the 19th and early 20th century can often alleviate this concern and put more recent measurements into context. In Boston, the rise in water levels during storms in 1851 and 1909 equaled an event in 1978 (**Figure 16**), and archival documents suggest that several other events in the 18th and 19th century were nearly equal. Hence, a risk assessment based on only modern data (1921–present) might underestimate the likelihood of recurrence. These data also demonstrate the importance of extreme tides—most of the flood events occurred during spring tides that exceeded Mean Higher High Water.

Quantitative measurements of water levels during storms (e.g., **Figure 16**) can become the basis for retrospective storm models and help anchor ensemble-based numerical methods in empirical reality. For example, Orton et al. (2016b) used quantitative estimates of the 1893 and 1821 hurricane events in New York City, combined with ensemble modeling, to reassess and improve storm surge hazard estimates.

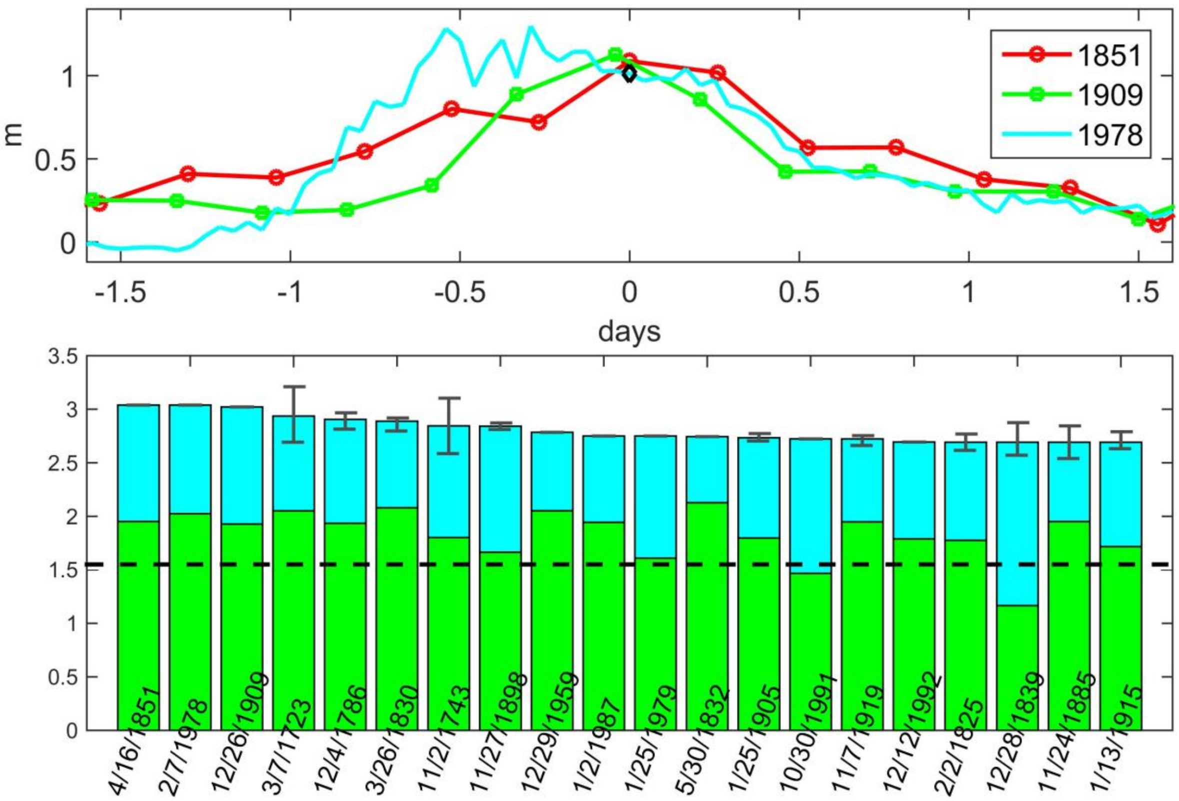


Figure 16. Top Panel: Skew surge (measured water level – predicted tide) of the top 3 extreme water level events in Boston, MA since 1825; Bottom Panel: Top 20 measured and estimated extreme water levels since 1723, measured in meters above the sea-level for that year. Values based on instrumental records and archival records. Removing contemporary sea-level helps elucidate the risk caused by tidal and meteorological forcing, without considering the effect of long-term changes to sea-level.

3.2 Changes to Tides

Deepened shipping channels, reclaimed wetlands, and hardened coastlines have changed the patterns and magnitudes of circulation and tidal flow in estuaries over the past century. In turn, these changes alter tidal range and affect tidal statistics and datums (e.g., Flick et al. 2003; Jay 2009; Woodworth 2010). Changes in oceanic circulation and stratification (e.g., Müller 2012) can also subtly affect tides, often complicating interpretation of long-term trends (e.g., in New York—see Talke et al. 2014).

Interestingly, the largest amplification in tidal range often occurs inland, far from the coast. In Wilmington, North Carolina, at River km 47, archival data indicates that tide range has doubled since the late 19th century (Familkhalili and Talke 2016). Similarly, recently recovered data from Albany, New York, (River km 230) indicates that tide range has more than doubled over the same time period (see **Figure 17**). In the fluvial part of the Ems Estuary, Germany, tidal range has increased by roughly 3 m since 1900 (Talke and Jay 2013). In all of these cases, much smaller (non-negligible) changes are noted close to the coast (Talke and Jay 2013; Talke et al. 2014). Though these examples are perhaps extreme, many estuaries have been significantly altered to accommodate shipping, leading to changes in tide amplitudes and phases. As an example, the M2 tide in Astoria has increased by ~5% since the 19th century; a significant change has also been observed in Philadelphia, with changes also observed in other harbors and coastal areas (**Figure 18**).

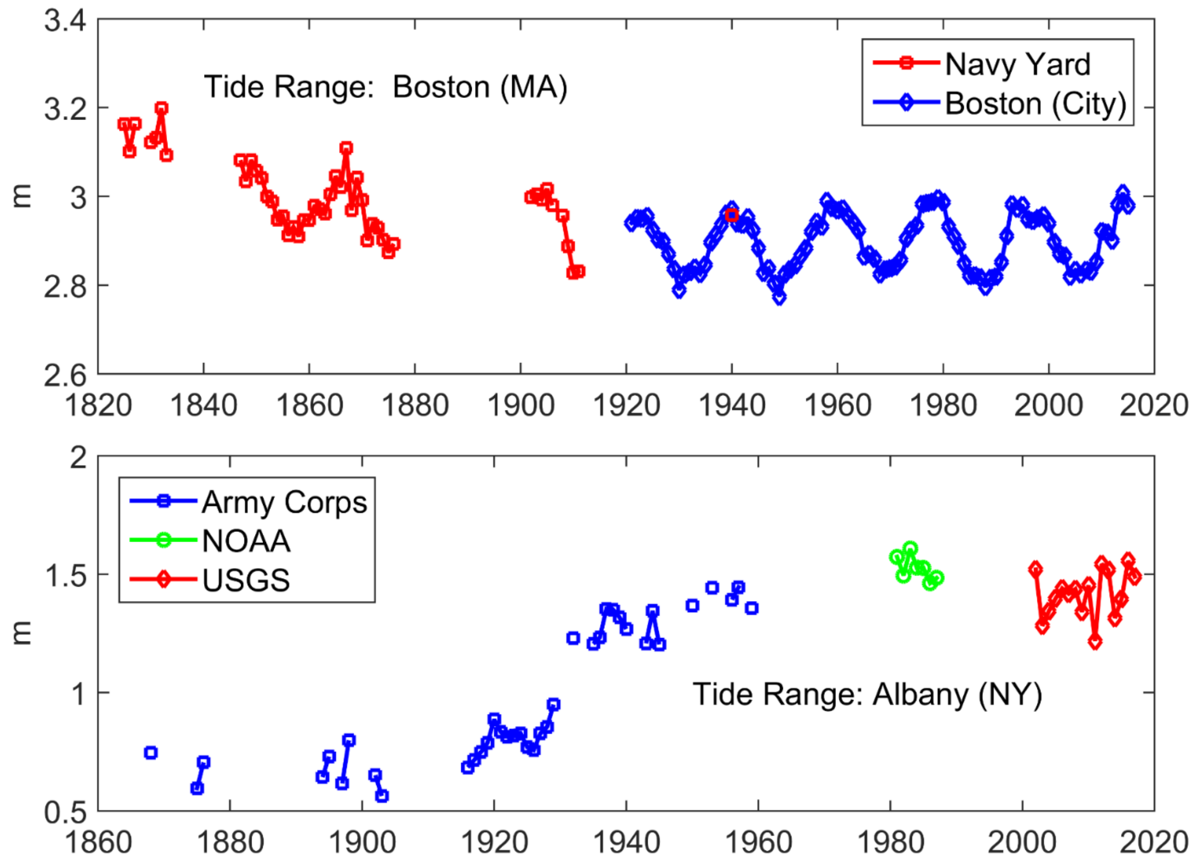


Figure 17. Change in Boston tidal range since 1824, and Albany (NY) tide range since 1868. Data at Albany is combined from Army Corps (blue), NOAA (green), and USGS (red) records. Boston data is compiled from tide gauges in the inner Boston harbor, including the Navy Yard (red), south Boston (1921-1939), and Boston proper (1939-present). The slightly different locations of the gages have a negligible effect on tide range (in this case).

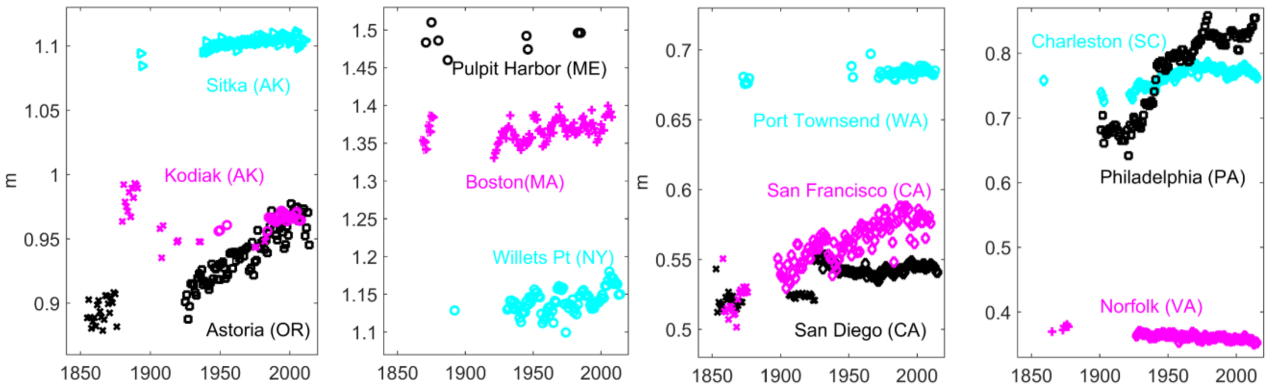


Figure 18. Change in the M2 tidal constituent all over the United States, based on the harmonic analysis of available and recovered hourly data. All 19th century data except San Francisco recovered from archives by the authors.

Two primary mechanisms, changed resonance and altered frictional damping, are often implicated in changing tides within harbors, estuaries, and rivers. Tidal resonance, caused by constructive interference between an incoming and reflected wave, can shift when the system depth or length is altered (e.g., Chernetsky et al. 2010; de Jonge et al. 2014; Familkhalili and Talke 2016; Kemp et al. 2017). Though only full reflections are typically considered (e.g., Bay of Fundy), partial reflections at headlands or depth transitions can also produce amplifications in tidal properties; hence when the characteristics of bathymetric transitions are altered, tidal changes may occur.

A decrease in frictional damping within a system over time often causes increased tidal amplitudes. Such changes can occur because of the removal of marshland (e.g., Orton et al. 2015) or decreased bottom roughness (Chernetsky et al. 2010) but are also observed when the system depth is increased (e.g., Chernetsky et al. 2010; Familkhalili and Talke 2016). This occurs because the effective friction on the tide wave is approximately proportional to the drag coefficient, but inversely proportional to depth (approximately; see Friedrichs and Aubrey 1994). Many other factors affect tidal properties, including changes to the width of the shipping channel (or the ratio of depth to width), the amount of subtidal and intertidal flats, the magnitude of river flow, and the rate of cross-sectional area convergence (see Jay 1991). Changes to mixing, turbulence, and circulation characteristics also influence tides (e.g., salinity intrusion, or wave breaking at a harbor entrance). Moreover, different factors interact non-linearly; for example, the resonant response of a system is altered by changes to frictional damping, all else being held equal (see e.g., Dronkers 1964).

Because the response of a tide to local bathymetry is complex, the hydrodynamic response of a system to bathymetric change can be non-intuitive. As an example, recently recovered measurements from Boston Harbor indicate that tide range has *decreased* by 5% over the last 2 centuries, despite channel deepening (**Figure 17**). A possible cause is extensive land reclamation that occurred between 1830 and 1930 and that produced "made land" such as Fenway Park or Logan Airport. A symptom of the wetland loss change is a collapse of the M6 overtide, and a shift in its relative phase with M2. Both of these changes partly explain the empirical observations, though changes to oceanic forcing cannot be ruled out. Hence, retrospective modeling is probably needed to fully understand observations.

3.3 Changes to Storm Surge

A recurrent hypothesis regarding climate change is that storms will become more intense, producing larger storm surges and extreme water levels. However, the hypothesis has been difficult to confirm empirically, perhaps because records are often not long enough to sample natural variability and obtain an ergodic signal. A signal is ergodic if the statistics of an individual time series are the same as ensemble averaged statistics. Such ensemble statistics would be found if repeated experiments of a recent period—say, 1980 to present—could be obtained. Modern modeling approaches allow for such ensemble statistics to be approximated through multiple simulations of the same historical time period—see Section 4.

Longer records found using digitized records may indicate whether risk is stable over time, or non-stationary. For example, recent analysis of the annual maximum water level in New York Harbor indicates that extreme water levels are increasing at a faster rate than changing sea levels (Talke et al. 2014). Since the mid-19th century, for example, the once-in-10-year extreme water level has increased by ~0.7m, outpacing the roughly 0.45m increase in sea level (**Figure 19**). In contrast, an analysis of the long Cuxhaven (Germany) record fails to find any long-term trends in storm surge since 1843, though climate-related fluctuations in risk are found (Dangendorf et al. 2014). Significant trends in the North Sea are found after ~1950, most likely due to changes in tidal amplitudes (Mudersbach et al. 2013).

Shifting storm characteristics or tracks are one explanation for long-term trends or fluctuations. Another hypothesis is that the same local changes that affect tides also affect storm surge. Essentially, a storm surge in an estuary or river behaves like a long wave with a wave-length that is much larger than the mean depth. Therefore, depth changes, friction changes, and resonance changes can also alter storm surge heights and the damping of surge within an estuary. We are currently investigating this hypothesis using modeling techniques (see Section 4).

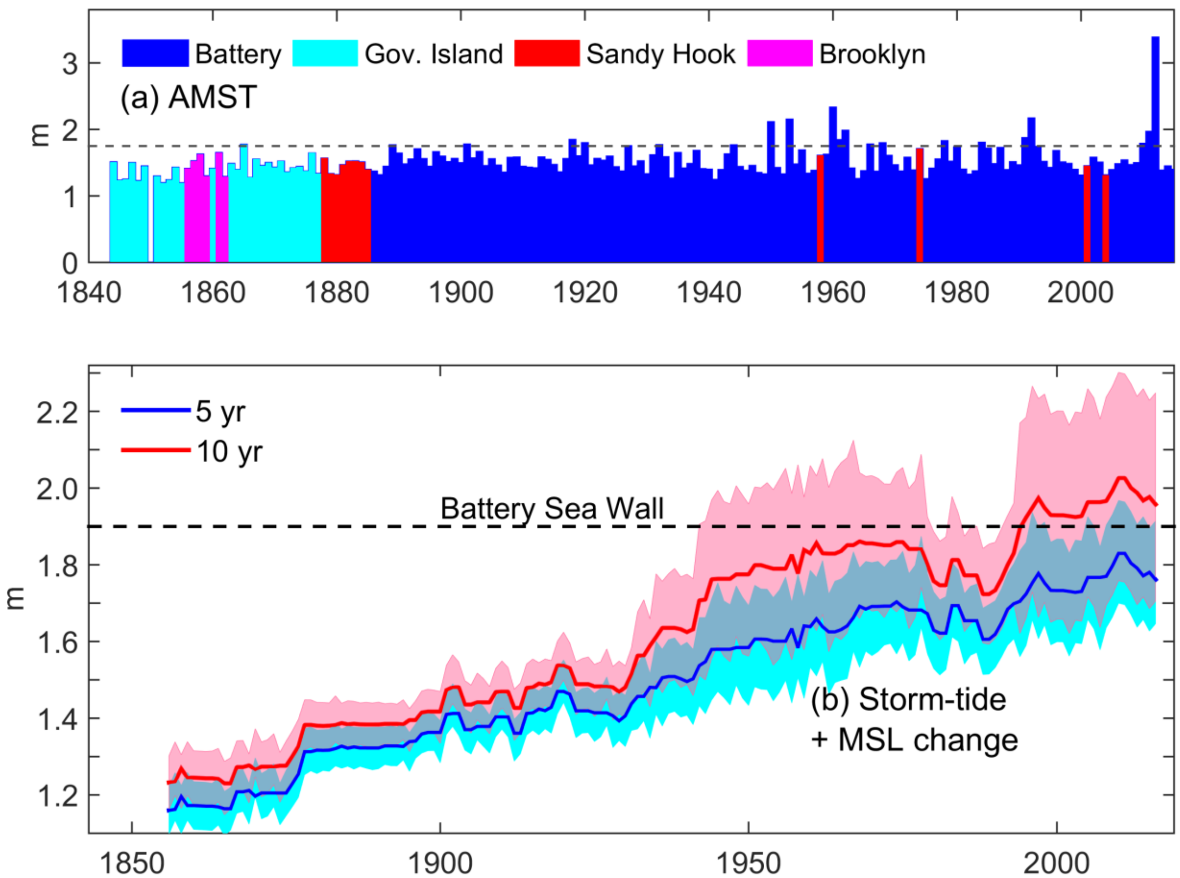


Figure 19. (a) Long term change in the Annual Maximum Storm Tide, defined as the maximum water level measured annually after annual mean sea-level is removed, and (b) the increase in the once in 5yr and once in 10yr extreme water level (relative to a fixed datum). Methods described in Talke et al., 2014. Here, the graphs have been updated to 2016 with NOAA data and newly found archival data.

3.4 Changes in Relative Local Sea Level

Historical water-level measurements can help constrain rates of changing sea levels and identify regions with local variability. Measurements of sea level available at NOAA show significant local and regional variability in the rates at which sea level is changing around the United States (NOAA 2012; Hall et al. 2016; NOAA 2017). Some areas, such as the U.S. East Coast, are subsiding and exhibit large rates of sea-level rise; Alaska, on the other hand, exhibits falling sea level due to tectonic uplift and glacial isostatic adjustment (GIA). Less appreciated is the observation that rates can vary significantly over small length-scales of 10–20 km, for example between Manhattan and Sandy Hook or San Francisco and Alameda, California. Data recovered from Astoria and Fort Stevens, Oregon, exhibit a roughly 0.2m/century difference in rates, despite being less than 15 km apart. The variability of vertical land motion may eventually be well assessed with modern Global Positioning Systems (GPS) and the tide gage network; however, in the meantime, recovery of historical data can reveal locations where rates of sea-level change diverge from known rates. Historical data may also help identify causes (e.g., water extraction) and quantify tectonically induced offsets.

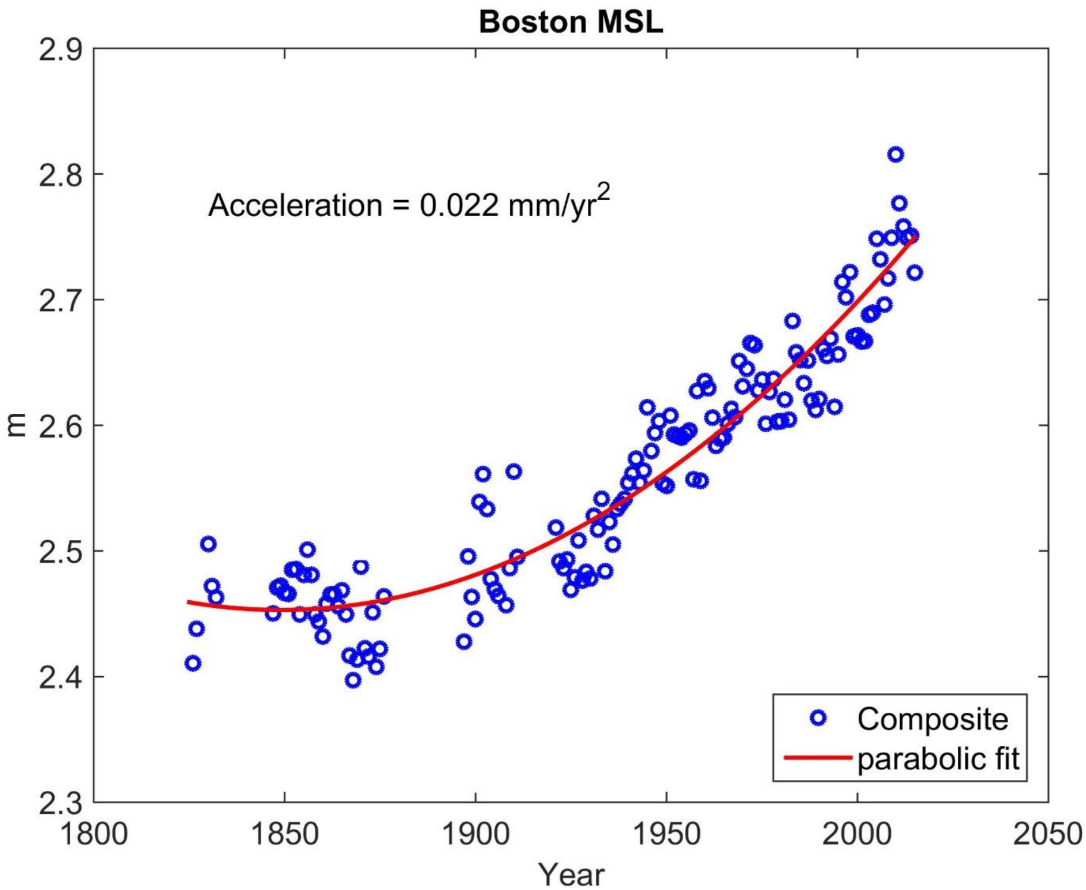


Figure 20. Boston Sea Level Rise, 1825-2016, from a composite of different gauge series at the Boston Navy Yard, the Commonwealth Pier, and the modern location. Data before 1921 recovered from archives, and plotted relative to the station datum of the modern NOAA gauge in Boston. The reported acceleration in MSL rise is twice the squared term in a parabolic fit.

In sum, historical data measured all over the United States (**Figures 2–8**) is producing a much longer record of local sea level at multiple stations. As shown in **Figure 20** above, longer measurements enable estimation of the acceleration in changing sea levels, along with modern trends. Moreover, such measurements address the paucity of 19th century data in sea-level reconstructions (e.g., Church and White 2011), and help constrain the accuracy of available measurements. For example, estimates of sea-level rise in Boston and New York since the mid-

19th century are found to agree to within about 0.05–0.06 m, after accounting for GIA. However, measurements also show that the coherence between the measurements decreases before 1870.

3.5 Changes to River Flow and Reconstruction of Historical Floods

As with storm tides, the "river flood of record" often occurred before modern measurements and is often poorly characterized (e.g., Moftakhari et al. 2013). For example, the January 1862 events in Northern California flooded much of the Central Valley and caused the state capital to move temporarily from Sacramento to San Francisco. However, as discussed in Hunsaker and Curran (2005), the exact amount of flow into San Francisco Bay is controversial, perhaps because of its implications for water management.

Historical tide gages can help quantify historical floods and flow statistics through a simple observation: tidal properties such as tide range are altered by river flows, to a degree that depends on the magnitude of river discharge (Kukulka and Jay 2003). Moftakhari et al. (2013, 2015, and 2016) developed several methods to estimate river flow based on historical tide data in San Francisco, the Columbia River, and the Fraser River in Canada. In Moftakhari et al. (2015), the tide gage-based reconstructions were used to quality check discharge estimates based on archival river-stage data (see map in **Figure 6**), and to infill missing data. Results showed that, in terms of total discharge over a 30-day period, the 1862 flood was ~25% larger than subsequent events (**Figure 21**; Moftakhari et al. 2013). However, on a daily basis, results suggest that the 1986 peak flow was slightly larger (Moftakhari et al. 2015). While some uncertainty is attached to any reconstruction, the instrumentally based assessments of Northern California hydrology show that flow events such as occurred in 1997 and 2017, which contributed to near failures at Oroville (2017) and Folsom dams (1997; personal communication, M. Dettinger), also occurred in the historical record. Notably, the 1862 flood served as the inspiration for the USGS ARkStorm modeling scenario (Porter et al. 2011), which (like 1862) consisted of back-to-back atmospheric river events (because of a lack of data on 1862, two modern storms from different years were modeled sequentially). Results were sobering: failure of the reservoir system, widespread flooding, and an estimated statewide cost of more than $700 billion. The use of archival tide data is clear and the data-based reconstruction of the 1862 discharge may enable future retrospective modeling of the actual event. Further, data from San Diego and Astoria may enable assessment of the entire coast (extensive flooding occurred throughout western Oregon but was not considered by Porter et al. 2011).

Overall, tide-based hindcasts of river flow can help elucidate non-stationarity in annual and seasonal river flow. In San Francisco, annual discharge to the ocean has decreased by ~30% since the 19th century (Moftakhari et al. 2013). Moreover, the seasonal distribution of flows into the Bay has changed over time (see also Knowles 2002). Historically, large flows occurred both in winter and during the spring snowmelt. In modern measurements, the spring snowmelt signal is small, because of a roughly 10% decrease in snowpack-driven flows (California Department of Water Resources [DWR] 2015) and because of the impounding effect of reservoirs (Knowles 2002). Tide-based flow reconstructions, which show a large historical variability in spring freshet magnitude, can potentially contribute to defining baseline environmental conditions. Indeed, an altered flow regime impacts sediment supply (Moftakhari et al.) and water quality variables such as water temperature, habitat inundation patterns (Jay et al. 2016), and salinity intrusion (Knowles 2002).

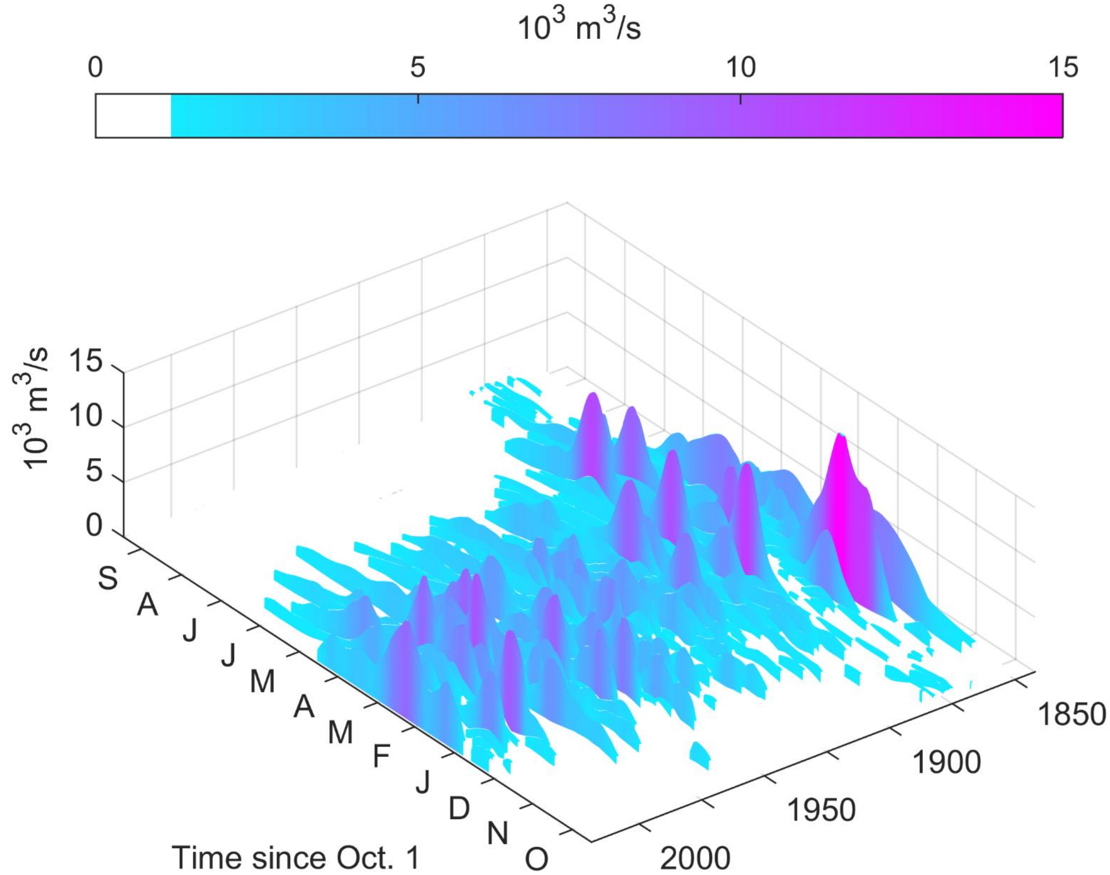


Figure 21. Changing inflow to SF Bay from 1849 to 2017. The 15-day averaged flow is based on the methods described in Moftakhari et al., (2013 & 2015), and modified to include discharge through April 2017.

3.6 Changes to River Slope and Effect on Extremes

Archival data recovery of tide and stage data in tidal rivers is suggesting that man-made changes to river depth and width have a surprising consequence. Conventional wisdom suggests that construction of dikes and loss of wetlands might concentrate all the water in the channel, raising river flood heights (as USACE 1995 and 2008 discuss, this is not always the case). However, the largest documented effect in many tidal rivers has been an increase in the occurrence of extreme low waters (e.g., Jay et al. 2011; Jensen et al. 2003); in other words, relative to a fixed datum, the elevation of the extreme low-water mark is now lower than in the past. The reasons are three-fold. First, peak river-flow volumes have often decreased because of upstream management (e.g., Jay and Naik 2011), reducing the probability of high waters. Second, channel deepening, dredging, and streamlining reduces the mean river slope by lowering hydraulic drag (e.g., Helaire 2016). This reduces water levels and is especially noticeable in fluvial stretches with a large surface slope (order 1 m per 100 km, or larger). For example, in the Portland/Vancouver Metro Area, the same Columbia River discharge today may yield mean water levels that are up to several meters lower than historically (e.g., Jay et al. 2011; Helaire 2016; **Figure 22**). Stated differently, the rating curve (water level versus discharge) at many locations now exhibits a lower slope and has shifted downward. Third, channelization and reduced drag has also amplified the tide range in rivers, especially at upstream locations (see Section 3.2, **Figure 17 & 18**). The superposition of decreased slope and increased tide range leads to amplified low-water extremes.

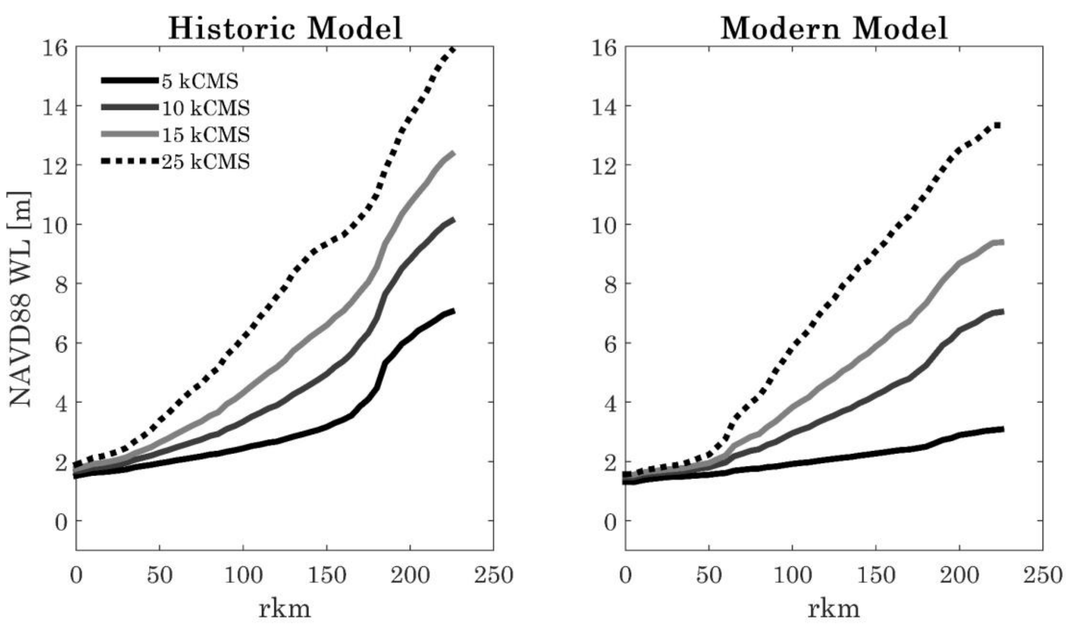


Figure 22. Comparison of water levels in the Columbia River Estuary for different constant inflow scenarios, using two separate numerical models that were developed using 19th century and modern bathymetry and data (see Helaire, 2016). The Ocean entrance is at River km 0, while the head of tides at Bonneville dam is at rkm 230. Historic water levels exceed modern levels for all modeled locations and river flows (from 5000 to 25,000 cubic meters per second). Both models were calibrated against tides and mean water levels from their corresponding time periods.

Interestingly, as discussed and explained in Jay et al. (2015), frictional effects damp spring tides more than neap tides. Hence, while the lowest tides in an estuary occur during spring tide conditions, the lowest extreme waters in tidal rivers often occur during neap tides. To explain, consider first that the flow velocity U in the lower estuary is larger during a spring tide than the ebb. Because frictional drag and energy dissipation are proportional to U^2 and U^3, respectively, more energy is dissipated during spring tides, resulting in an enhanced reduction of the tide wave as it travels upstream, compared to the neap tide. River flow also influences the friction by producing larger total velocities, again producing a larger effect on spring tides (see also Kukulka and Jay 2003). Stratification during neap tides reduces the energy dissipation in the estuary. Altogether, the enhanced friction during a spring tide produces a larger river slope, while reducing the spring tide amplitude. The result is the curious observation that *neap water levels are often lower than spring tides in the upstream portions of a tidal river*.

The discussion above applies to the typical range of river discharge observed in a managed system. Modeling studies are required to answer a slightly different question: *If the historical flood of record occurred today, would it produce smaller or larger water levels than historically?* A retrospective numerical model based on digitized historical bathymetry, and calibrated against archival tide and river stage data, can be used to address this question (e.g., Helaire 2016). In the tidal Columbia River, many spring-freshets overtopped the natural levees and inundated the floodplain; this leads to a decrease in the stage versus flow curve at high flows in historical data (Helaire 2016). Because constructed levees are built higher than natural levees, one might expect less floodplain inundation and larger heights. However, model results suggest that the historical floodplain, which was covered by alders, spruce, and dense vegetation, was so frictional that it conveyed little flow or momentum. As a result, historical flow, like today, was primarily confined to channels and seems to have been higher than modern levels would be, even in extreme conditions (Helaire 2016). After the 1993 flood on the Mississippi River, a USACE study (1995) found a similar result—removing levees produced little or no benefit to flood heights if the floodplain was covered by historical vegetation (interestingly, more than 1m of reduction was found if the floodplain remained cleared and unvegetated). Therefore, though increased stages have been observed in some river systems such as the Missouri at St. Louis, there is no consensus regarding whether these increases can be attributed to the presence of levees alone or whether other factors are important, such as antecedent moisture, increased heavy precipitation, river regulation, and land-use practices (USACE 1995). In the future, more detailed studies in other regions are needed to address the important question of whether a modern flood could exceed historical high-water marks, given the same flow.

4. Synergies of Using Historical Data with Modeling

Historical data recovery provides empirical evidence of past extreme events and enables assessment of long-term trends in tides, storm surge, and risk (Section 3). As shown in **Figures 2–9**, data recovery may also fill gaps in spatial data coverage. Nonetheless, the full power of historical data is harnessed when combining it with modern analyses including numerical modeling to estimate spatial and temporal variability and trends.

Several different strategies of numerical modeling can be applied in conjunction with historical data, each with advantages and disadvantages. First, idealized modeling—in which a simplified version of the coastal system is studied—enables multiple sensitivity studies to be performed that investigate the effect of individually changing just one parameter such as depth or wind speed (e.g., Familkhalili and Talke 2016). Second, fully resolved numerical models with historical boundary conditions and bathymetry can be used to assess historical tides, storm surge events, and flood events. Such retrospective modeling, combined with experimental sensitivity studies, can assess how actual system alterations—such as loss of wetlands or changing sea levels—have altered system functioning (e.g., Orton et al. 2015; Brandon et al. 2016; Helaire 2016; Kemp et al. 2017). Moreover, the knowledge gained in studying these historical changes can be applied to developing new nature-based concepts for flood risk reduction (e.g., Orton et al. 2016a). Finally, historical data can be used to validate models for rare extreme events in ensemble-based assessments of storm surge risk (Orton et al. 2016b).

4.1 Idealized Modeling: Channel Deepening and the Cape Fear Estuary

Idealized analytical, 1D, and 2D models have often been used to explain how tides in estuaries and rivers can change over time (Amin 1983; Chernetsky et al. 2010; de Jonge et al. 2014). The explanatory reach of such models is made more powerful by combining sensitivity studies with analysis of historical tide data (e.g., de Jonge et al. 2014). As an example of the fusion of archival data with retrospective modeling, Familkhalili and Talke (2016) recovered and digitized about 30 years of archival tide data in the Cape Fear Estuary, North Carolina, back to the 1880s. These data showed two essential facts: (1) tide range had doubled in Wilmington, North Carolina (River km 47) over time and (2) coastal tide range had stayed approximately the same. To test the hypothesis that storm tides also changed, Familkhalili and Talke (2016) created an idealized, funnel-shaped approximation of the Cape Fear Estuary. By running multiple, parametrically generated hurricanes over different tide and depth scenarios, Familkhalili and Talke (2016) showed that doubling the channel depth from 8 m to 16 m likely produced a large change in flood risk in Wilmington (River km 47; **Figure 23**). Model experiments were used to demonstrate that the majority of tide changes were likely caused by channel deepening and not by other alterations (such as bottom roughness).

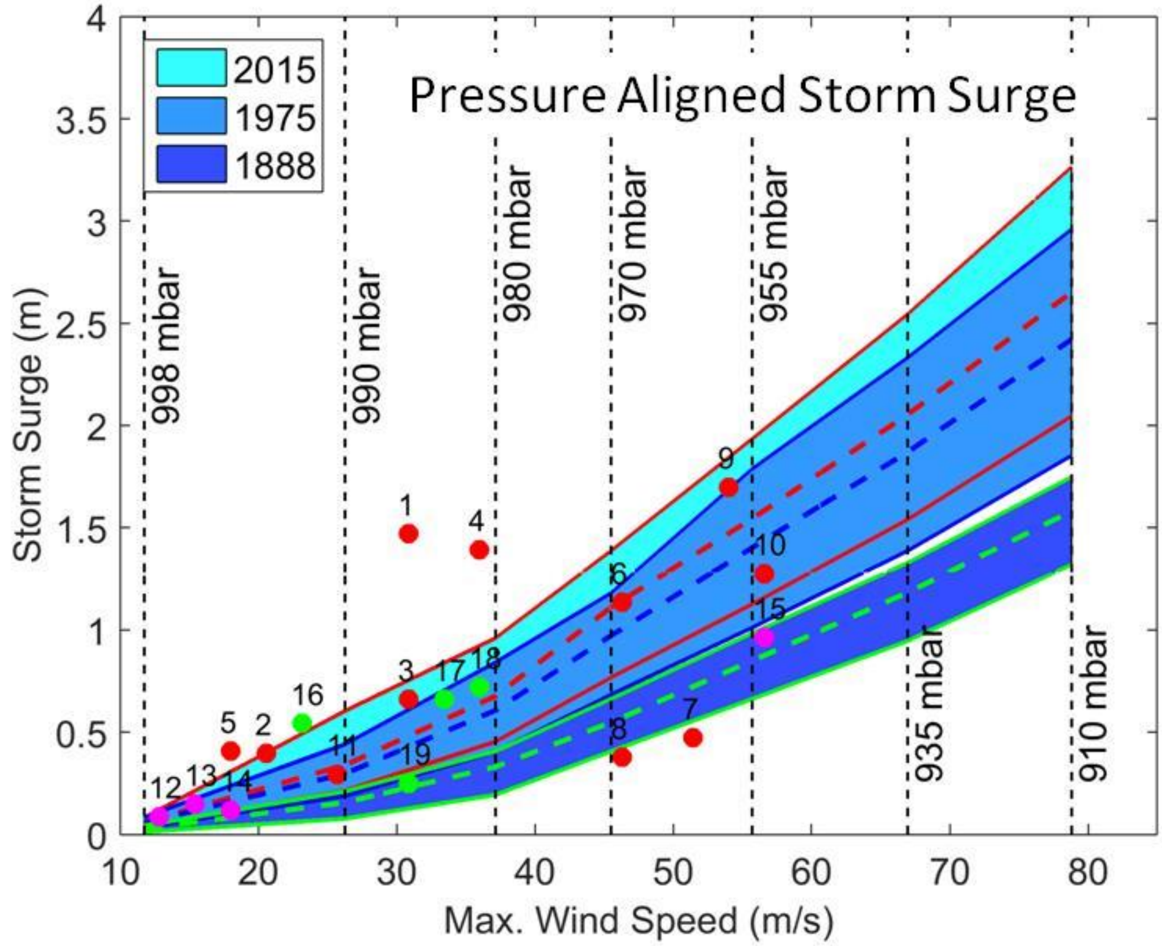


Figure 23. Change in modeled storm surge risk caused by channel deepening (modified from Familkhalili & Talke, 2016). The x-axis refers to the severity of the storm; the 910 mbar case is a category 5 storm. The low pressure of the storm was modeled to go up the center axis of an idealized, funnel shaped estuary. The dots refer to storm surge caused by actual tropical cyclones, and were used to show that the idealized modeling plots are plausible. The fill plots refer to different idealized modeling scenarios. As can be seen, storm surge water levels in the 1975 and 2015 scenarios are much higher than the 1888 scenario for all types of cyclones.

4.2 Realistic Modeling and Historical Data: Deep Validation

When combining archival data with retrospective modeling, models can be challenged to reproduce the trajectory from the **historical state A** to the **modern state B**. This can be attempted with idealized modeling that approximates different states (e.g., Familkhalili and Talke 2016) or with realistic, detailed modeling that attempts to reproduce the exact historical observations. Models that reproduce present-day tides or flood events are often considered to have been "validated," yet if only modern conditions are modeled, it is possible to get the right answer for the wrong reasons, undermining projections or conclusions. A more complete, "deep validation" of a model attempts to reproduce conditions over different historical periods, with different bathymetry and forcing. Only by reproducing empirically measured changes to water levels can we be certain that parameter values (such as bed friction) are reasonable and that we are including all relevant processes and changes (to river flow, bathymetry, wave climate, and so on). This demonstrates one of the synergistic benefits of a combined historical data recovery and modeling approach, which is able to overcome the limitations of a model (insufficient validation) and data (insufficient explanatory power).

Once we are confident a model has performed acceptably with a deep validation of past and present states, we can begin to address whether it will succeed in modeling future states, e.g., **future state C**. In this way, recovering and using historical tide data can improve validation of the scenario-based modeling that is often used to plan for the future. Studies of future states investigate the effect of different management or climate scenarios and are tested by altering bathymetry or boundary conditions. For example, Arns et al. (2017) altered the existing bathymetry to test how sea-level changes would alter tides, storm surge, and wave run-up. Similarly, Orton et al. (2015) investigated the effect of different restoration scenarios in Jamaica Bay on storm surge risk (**Figure 24**). While restoring wetlands produced little effect on the modeled extreme water levels, decreasing channel depths to historical norms resulted in a significant reduction. In particular, channel shallowing reduced the estimated water level from a fast-moving storm such as the 1821 hurricane by 1.3 m or ~50% (less protection was observed for slow-moving storms such as Sandy). Hence, restoring systems to their natural depths can sometimes mitigate against extreme events and provides another possible tool in the arsenal of engineering solutions available.

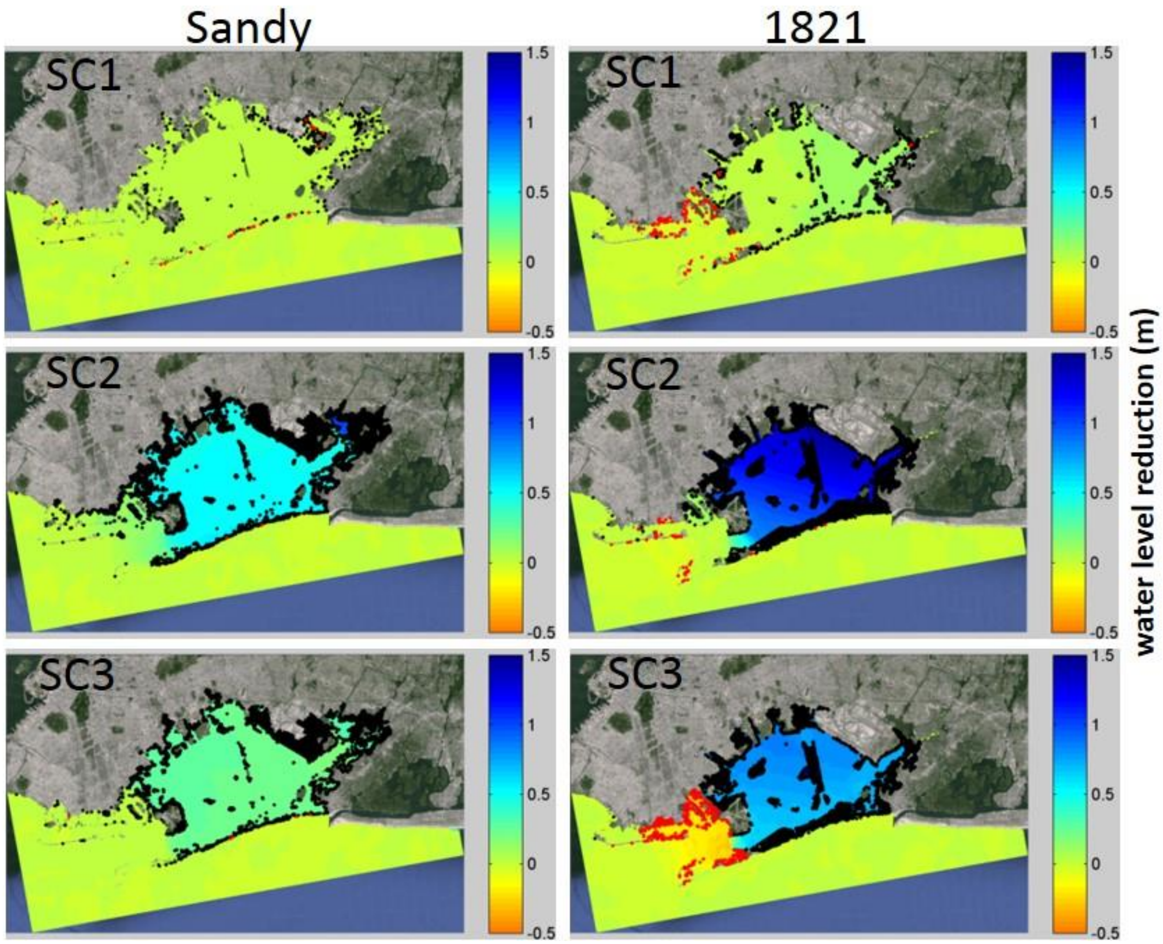


Figure 24. Reductions in modeled peak water level in Jamaica Bay, NY, using three landcover/bathymetry scenarios (SC1, SC2, and SC3) and wind forcing from two extreme tropical cyclones: Hurricane Sandy (2012) and the September 1821 Hurricane. Scenario SC1 shows that restoring wetlands everywhere produces a minor effect on water levels, whereas shallowing the shipping channels from 8m to historical levels of 1-2m (SC2) produces a large reduction in storm surge. Scenario 3 is the reduction that occurs by only shallowing the inlet. Figure adapted from Orton et al., 2015.

Historical data recovery can help validate such scenario-based modeling. Though the Jamaica Bay model result described above is indirectly supported by observations in other estuaries (e.g., Section 4.1), empirical measurements from 1877 and 1878 demonstrate that the tidal range was ~35% smaller before channel deepening occurred in the early 20th century. By confirming that the numerical model is reproducing the observed changes in tides, we now have more confidence that various parameters such as bed friction are being correctly applied. Helaire (2016) used a similar procedure to validate a retrospective model of the 19th century Columbia River. In particular, the tidal variability and damping in the river during low-flow conditions was validated using data from an 1877 hydrographic survey, while a rating curve set to recovered data in

Portland, Oregon, was used to calibrate the high-flow response. This data-based approach helped correctly model poorly known features of the system such as the height of natural levees and the bed friction of the floodplain.

These examples show that even short-data series can help calibrate models and validate their results. As discussed in Section 2, such short-time series were measured virtually everywhere around the U.S. coast during the 19th and early 20th century, in support of bathymetric surveys. The results of such tidal surveys are often found on original maps, but the actual data are also still available (see Section 2). As more historical data are recovered, the possibility exists to validate and improve studies such as Orton et al. (2015) by comparing directly with historical data. In turn, historical data, because they reflect more natural conditions, can be used to help validate the efficacy of mitigation and restoration efforts, or nature-based solutions to flood risk reduction.

4.3 Ensemble-based Modeling and Historical Data

The increasing power of numerical models has made possible the use of ensemble modeling techniques in risk assessment. In such approaches, a family of synthetic storms (e.g., tropical cyclones) is randomly generated using present-day climate conditions and is then allowed to develop and produce a storm surge (e.g., Lin et al. 2012, 2016). By sampling hundreds, thousands, or even millions of events, such techniques potentially produce a simulated data set that reflects a representative range of natural possibilities. For example, the unusual left turn of Hurricane Sandy in October 2012 had never been observed in empirical data before 2012 but does occasionally occur in ensemble modeling (Hall and Sobel 2013). The potential gains of using ensemble modeling are therefore clear. However, synthetic modeling may miss combination events, such as when a hurricane produces flooding from both storm surge and river flooding (e.g., Hurricane Irene in 2011).

Moreover, without careful validation, ensemble modeling can potentially produce unrealistic results and become counter-factual. To combat this, studies such as Arns et al. (2017) and Orton et al. (2016b) combine ensemble-based modeling with retrospective modeling of historical storms. In Orton et al. (2016b), 42 archival storms with different tracks, wind speeds, propagation speeds, and size were run to make sure that the numerical model was working well under different tide and storm conditions. This approach helped validate parameter values such as the maximum friction coefficient between wind and water. Having shown that the model worked well for a representative set of large historical events, Orton et al. (2016b) next subsampled a numerically generated database of synthetic storms, ultimately testing more than 1,500 events. The combined approach generated return-period estimates of large events such as Hurricane Sandy that are more robust than previous estimates.

4.4 Modeling and Assessing the Effects of Changing Sea Level

A commonly applied planning technique for estimating future performance and reliability of designs is to assess present-day risk using modern data. The non-stationary responses of tides and storm surge to historical changes (Sections 3 & 4) suggest that the response of a system to changing sea levels is often non-linear. In fact, Arns et al. (2017) showed that tides, storm surge, and especially wave run-up changed dramatically with changing sea levels, requiring dike heights on the German coast to rise at twice the local changing sea levels.

Nevertheless, projections of possible future conditions are dependent on assumptions. For example, Arns et al. (2017), while conceptually correct, does not include possible morphodynamic feedback that might mitigate—or accelerate—the deepening of intertidal flats caused by changing sea levels. Therefore, while Arns et al. (2017) convincingly argue that ignoring increased wave-run up is dangerous, the exact amount of change remains difficult to predict.

In this context, the retrospective modeling described in earlier sections is instructive. Past is preview; hence, the hypothesis that changing sea levels may produce a reduction in the slope of the Columbia River is made plausible by the quantifiable historical response of the system. As shown in **Figure 22**, numerical modeling shows that channel deepening of the Columbia River (from a controlling depth of ~8 m to ~16 m) has produced lower water levels throughout the estuary for any given flow, particularly in the upstream reaches. Because the retrospective, 19th century numerical model and the modern 21st century model were both extensively calibrated to match historical tides and mean water levels throughout the system (see Helaire 2016), the system response to depth changes has been quantified. Therefore, initial modeling results that show that sea-level rise may produce a similar response (a lowering of river slope) is plausible. The complexities of a real system—such as long-term changes to sediment supply and the resulting morphodynamic response (see Moftakhari et al. 2015; Jay and Templeton 2012)—must also be considered. Similarly, Arns et al. (2017) was able to explain increases in modeled tides by pointing to similar observations over the past 50 years. Therefore, retrospective modeling can help validate and improve models, or at the minimum reveal their weaknesses and the unknowns and assumptions necessary to model future conditions.

5. Conclusions and Next Steps

Historical tide data were collected over the last 200 years in coastal regions of the United States, and only a portion has been digitized. This report details efforts to find and catalog historical tide data and shows that these data can help indicate the degree to which oceanic changes or local anthropogenic changes have altered system properties. The types of changes that tide measurements (often in combination with modeling) can help elucidate include:

- Changes to tides and tidal datum such as tide range or MHHW (Mean Higher High Water)
- Alterations in storm surge waves, for the same meteorological forcing
- Alterations in flood wave behavior, for the same river forcing
- Alterations in river slope, for the same river flow
- Long-term changes to river flow
- Changes in sea levels, as well as local variability in subsidence & uplift.
- Altered meteorological forcing.

Improved performance and reliability of coastal assets under changing conditions can be produced by considering possible changes to the entire water-level spectrum, rather than just changing sea levels. Historical tide measurements help provide the instrumental data and context required to validate models and evaluate the effect of possible future scenarios. Elucidating the types of feedback mechanisms that occur in harbors, rivers, and coastal regions remains an area of active research. In particular, the morphodynamic response of estuaries is poorly known. Similarly, the system-scale effect of future human interventions is unknown. For all such reasons, continued recovery and digitization of data is necessary.

6. Acknowledgements

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7. References

Agnew, D. A. 1986. Detailed analysis of tide gage history: A case analysis. *Marine Geodesy*, vol. 10, issue 3–4, pp. 231–255.

Amin, M. 1983. On perturbations of harmonic constants in the Thames Estuary. *Geophys. J. R. Astr. Soc.*, vol. 73, pp. 587-603.Arns, A., J. Bender, S. Dangendorf, J. Jensen, C. Pattiaratchi, and S. A. Talke. 2017. Sea-level rise induced amplification of coastal protection design heights. *Nature: Scientific Reports*, doi:10.1038/srep40171.

Brandon, C. M., J. P. Donnelly, P. M. Orton, and J. D. Woodruff. 2016. Evidence for elevated coastal vulnerability following large-scale historical oyster bed harvesting. *Earth surface processes and landforms.* doi:10.1002/esp.3931.

Bromirski, P. D., D. R. Cayan, and R. E. Flick. 2003. Storminess variability along the California coast: 1858–2000. *J. Climate*, vol. 16, issue 6, pp. 982–993.

Burgette, R. J., D. A. Schmidt, and R. J. Weldon II. 2009. Interseismic uplift rates for western Oregon and along-strike variation in locking on the Cascadia subduction zone. *J. Geophys. Res.*, vol. 114, B01408, doi:10.1029/2008JB005679.

CDWR (California Department of Water Resources). 2015. Hydroclimate report, water year 2015.

Chernetsky, A. S., H. M. Schuttelaars, and S. A. Talke. 2010. The effect of tidal asymmetry and temporal settling lag on sediment trapping in tidal estuaries. *Ocean Dyn.*, vol. 60, pp. 1219–1241, doi:10.1007/s10236-010-0329-8.

Church, J. A., and N. J. White. 2011. Sea-level rise from the late 19th to the early 21st century. *Surveys in Geophys.*, vol. 32, issue 4–5, pp. 585–602.

Dangendorf, S., J. Jensen, S. Müller-Navarra, F. Schenk, T. Wahl, and R. Weisse. 2014. North Sea storminess from a novel storm surge record since AD 1843. *J. Climate*, vol. 27, issue 10, pp. 3582–3595.

Devlin, A., D. A. Jay, S. A. Talke, and E. D. Zaron. 2014. Tidal trends associated with anomalous sea level rise in the western Pacific Ocean. *Ocean Dyn.*, vol. 64, pp. 1093–1120, doi:10.1007/s10236-014-0741-6.

Dronkers, J. J. 1964. Tidal *computations in rivers and coastal waters, North-Holland, Amsterdam*. New York: Interscience (Wiley), 518 pp.

Familkhalili, R, and S. A. Talke. 2016. The effect of channel deepening on storm surge: A case study of Wilmington, NC. *Geophysical research letters*, doi:10.1002/2016GL069494.

Flick, R., L. Ewing, and J. Murray. 2003. Trends in United States tidal datum statistics and tide range. *J. Waterw. Port Coastal Ocean Eng.*, vol. 129, issue 4, pp. 155–164, doi:10.1061/(ASCE)0733-950X(2003)129:4(155).

Freeman, J. R., Massachusetts, 1903. *Committee on Charles River Dam; Report of the Committee on Charles River Dam, appointed under resolves of 1901, chapter 105, to consider the advisability and feasibility of building a dam across the Charles River at or near Craigie bridge*. *Appendix 20*. Boston: Wright and Potter Printing Co., State Printers.

Friedrichs, C. T., and D. G. Aubrey. 1994. Tidal propagation in strongly convergent channels. *J. Geophys. Res.*, vol. 99, pp. 3321–3336, doi:10.1029/93JC03219.

Furlong, L. 1796. *The American coast pilot*. Newburyport, MA: Blunt & March. Hall, J. A., S. Gill, K. Knuuti, J. Marburger, J. Obeysekera, and W. Sweet. 2016. Regional sea level scenarios for coastal risk management: Managing the uncertainty of future sea level change and extreme water levels for Department of Defense coastal sites worldwide. U.S. Department of Defense, Strategic Environmental Research and Development Program. 224 pp.

Hall, T.M., and A. H. Sobel. 2013. On the impact angle of Hurricane Sandy's New Jersey landfall. *Geophys. Res. Lett.*, vol. 40, pp. 2312-2315, doi:10.1002/grl.50395.

Harris, D., and C. Lindsay. 1957. *An index of tide gages and tide gage records for the Atlantic and Gulf coasts of the United States*. National Hurricane Research Project Report No. 7.

Helaire, L. T. 2016. Modeling of historic Columbia River flood impacts based on Delft 3D simulations. Master's thesis, Portland State University.

Hickson, R. E. 1912. A report on the establishment of river gages on lower Columbia & Willamette rivers. Report to the U.S. Army Corps of Engineers.

HRA (Historical Records Survey). 1937. *Inventory of federal archives in the states*. Series IV. The Department of War. Prepared by the Survey of Federal Archives, Division of Women's and Professional Projects, Works Progress Administration. The National Archives, cooperating sponsor.

Hudson, A. S., R. Branch, C. Chickadel, G. Farquharson, A. Jessup, and S. A. Talke. 2017. Remote measurements of tides and river slope using airborne lidar instrument. *J. Atmos. and Ocean. Tech.*, vol. 34, issue 4, pp. 897–904, *http://dx.doi.org/10.1175/JTECH-D-16-0197.1*.

Hunsaker, L., and C. Curran. 2005. *Lake Sacramento: Can it happen again?* Grants Pass, OR: Copy Quick & Academy Printing.

IHR (International Hydrographic Review), 1932. Vol. 9. Monaco: International Hydrographic Bureau.

Jay, D. A. 1991. Green's Law revisited: Tidal long wave propagation in channels with strong topography. *J. Geophys. Res*., vol. 96, issue 20, pp. 585–598.

Jay, D. A. 2009. Evolution of tidal amplitudes in the eastern Pacific Ocean. *Geophys. Res. Lett.*, vol. 36, L04603, doi:10.1029/2008GL036185.

Jay, D. A., and P. K. Naik. 2011. Distinguishing human and climate influences on hydrological disturbance processes in the Columbia River, USA. *Hydrol. Sci. J.*, doi:10.1080/02626667.2011.604324.

Jay, D. A., S. Degens, and K. Leffler. 2011. Long-term evolution of Columbia River tides, ASCE. *J. Waterway, Port, Coastal, and Ocean Eng.*, vol. 137, pp. 182–191, doi:10.1061/(ASCE)WW.1943-5460.0000082.

Jay, D. A., A. Borde, H. Diefenderfer, and K. Leffler. 2015. Tidal-fluvial and estuarine processes in the Lower Columbia River: Part I: Along-channel water level variations, Pacific Ocean to Bonneville Dam. *Estuaries and Coasts*, vol. 38, pp. 415–433, doi:10.1007/s12237-014-9819-0.

Jay, D. A., A. Borde, and H. Diefenderfer, 2016. Tidal-fluvial and estuarine processes in the Lower Columbia River: Part II: Water Level Models, Floodplain Wetland Inundation, and System Zones. *Estuaries and Coasts*, vol. 39 https://doi.org/10.1007/s12237-016-0082-4

Jensen, J. C., C. J. Blasi, and C. Mudersbach. 2003. Hydrological changes in tidal estuaries due to natural and anthropogenic effects. 6th International MEDCOAST 2003 Conference, Ravenna, Italy.

de Jonge, V. N., H. M. Schuttelaars, H. E. de Swart, S. A. Talke, and J. M. M. Van Beusekom. 2014. The influence of channel deepening on estuarine turbidity dynamics, as exemplified by the Ems estuary. *Estuary, Coastal and Shelf Sci.*, vol. 139, pp. 46–59. Kemp, A., C. Bernhardt, N. Cahill, E. K. Hartig, T. D. Hill, P. M. Orton, A. C. Parnell, K. Sanborn, S. A. Talke, and C. H. Vane. 2017. Relative sea-level trends in New York City during the past ~1500 years. *The Holocene,* doi/full/10.1177/0959683616683263.

Knowles, N. 2002. Natural and management influences on freshwater inflows and salinity in the San Francisco Estuary at monthly to interannual scales. *Water Resources Research*, vol. 38, issue 12, pp. 25.1–25.11, doi:10.1029/2001WR000360.

Kukulka, T., and D. A. Jay. 2003. Impacts of Columbia River discharge on salmonid habitat: Part 1. *J. Geophys. Res*., vol. 108, issue C9, p. 3293, doi:10.1029/2002JC001382.

Lin, N., K. Emanuel, M. Oppenheimer, and E. Vanmarcke. 2012. Physically based assessment of hurricane surge threat under climate change. *Nat. Clim. Change*, vol. 2, pp. 462–467, doi:10.1038/nclimate1389.

Lin, N., J. P. Donnelly, B. P. Horton, and R. E. Kopp. 2016. Hurricane Sandy's flood frequency increasing from year 1800 to 2100. *PNAS*, vol. 113, issue 43, pp. 12071–12075; doi:10.1073/pnas.1604386113.

Manning, T. G. 1988. *U.S. Coast Survey vs. Naval Hydrographic Office: A 19th-century rivalry in science and politics*. Tuscaloosa, AL: University of Alabama Press, 202 pp.

Moftakhari, H. R., P. D. Bromirski, D. A. Jay, T. Kukulka, and S. A. Talke. 2013. A novel approach to flow estimation in tidal rivers. *Water Resources Research*, vol. 49, pp. 1–16, doi:10.1002/wrcr.20363.

Moftakhari, H. R., D. A. Jay, D. H. Schoellhamer, and S. A. Talke. 2015. Estimation of historic flows and sediment loads to San Francisco Bay, 1849–2011. *J. Hydrol.*, 529, pp.1247-1261, doi:10.1016/j.jhydrol.2015.08.043\.

Moftakhari, H. R., D. A. Jay, and S. A. Talke. 2016. Estimating river discharge using multiple-tide gages distributed along a channel. J. Geophys. Res., Oceans, vol. 121, doi:10.1002/2015JC010983.Mudersbach, C., I. D. Haigh, J. Jensen, and T. Wahl. 2013. Trends in high sea levels of German North Sea gages compared to regional mean sea level changes. Cont. Shelf Res., vol. 65, pp. 111–120, doi:10.1016/j.csr.2013.06.016.

Müller, M. 2012. The influence of changing stratification conditions on barotropic tidal transport and its implications for seasonal and secular changes of tides. Cont. Shelf Res., doi:10.1016/j.csr.2012.07.003.

NOAA (National Oceanic and Atmospheric Administration). 2012. Global sea level rise scenarios for the United States. National Climate Assessment. NOAA Technical Memo OAR CPO-1.

NOAA, 2017. Global and regional sea level rise scenarios for the United States. NOAA Technical Report NOS CO-OPS 083.

Orton, P. M., A. F. Blumberg, N. Georgas, D. A. Jay, K. MacManus, H. J. Roberts, S. A. Talke, L. Yin, and H. Zhao. 2015. Channel shallowing as mitigation of coastal flooding. *J. Marine Sci. and Eng.*, vol. 3, issue 3, pp. 654-673, doi:10.3390/jmse3030654.

Orton, P., K. MacManus, E. Sanderson, J. Mills, M. Giampieri, K. Fisher, and G. Yetman. 2016a. Project Final Technical Report: Quantifying the value and communicating the protective services of nature-based flood mitigation using flood risk assessment, http://adaptmap.info/jamaicabay/technical_report.pdf.

Orton, P. M., A. F. Blumberg, N. Georgas, T. M. Hall, S. A. Talke, and S. Vinogradov. 2016b. A validated tropical-extratropical flood hazard assessment for New York Harbor. *J. Geophys. Res.*, doi:10.1002/2016JC011679.Porter, K., C. Alpers, A. Baez, P. Barnard, J. Carter, A. Corsi, J. Costner, D. Cox, T. Das, M. Dettinger, J. Done, C. Eadie, M. Eymann, J. Ferris, P. Gunturi, M. Hughes, R. Jarrett, L. Johnson, H. D. Le-Griffin, D. Mitchell, S. Morman, P. Neiman, A. Olsen, S. Perry, G. Plumlee, M. Ralph, D. Reynolds, A. Rose, K. Schaefer, J. Serakos, W. Siembieda, J. Stock, D. Strong, I. Sue Wing, A. Tang, P. Thomas, K. Topping, A. Wein, and C. Wills. 2011. Overview of the ARkStorm scenario. U.S. Geological Survey Open-File Report 2010-1312.

Rappleye, H. S. 1932. *Leveling in Oregon*. Special Publication No. 177, Washington, DC: U.S. Coast and Geodetic Survey.

Ray, R. D., and G. Foster. 2016. Future nuisance flooding at Boston caused by astronomical tides alone. *Earth's Future*, vol. 4, pp. 578–587, doi:10.1002/2016EF000423.

Reidy, M. S. 2008. Tides of history: Ocean science and Her Majesty's Navy. University of Chicago Press, 392 pp.

Smith, B. W. 1997. Meteorological and tide stations, 1890–1917. *The Coast Defense Study Group J.*, Feb. 1997, pp. 23–36.

Talke, S. A., and D. A. Jay. 2013. Nineteenth century North American and Pacific tides: Lost or just forgotten? *J. Coast. Res.*, vol. 29, issue 6a, pp. 118–127.

Talke, S. A., D. A. Jay, and P. Orton. 2014. Increasing storm tides in New York Harbor, 1844–2013. *Geophys. Res. Lett.*, vol. 41, issue 9, pp. 3149–3155, doi:10.1002/2014GL059574.

USACE (United States Army Corps of Engineers). 1995. Flood plain management assessment of the upper Mississippi River and lower Missouri tributaries.

USACE. 2008. Draft Supplemental environmental impact statement: Mississippi River between the Ohio and Missouri rivers (regulating works). U.S. Army Corps of Engineers, St. Louis District.

Woodworth, P. L. 2010. A survey of recent changes in the main components of the ocean tide. Cont. Shelf Res., vol. 30, issue 15, pp. 1680–1691, doi:10.1016/j.csr.2010.07.002.

Zaron, E. D., and D. A. Jay. 2014. An analysis of secular change in tides at open-ocean sites in the Pacific. J. Phys. Oceanogr., vol. 44, issue 7, pp. 1704–1726, doi:10.1175/JPO-D-13-0266.1.